SECTION 13—MARINE SYSTEMS TECHNOLOGY

Scope

Highlights

- At the same power levels, the intercooled recuperated gas turbine will use 30 percent less fuel than a simple-cycle gas turbine (Section 13.2).
- Heat engine air-independent propulsion (AIP) systems, despite limitations, will extend the submerged endurance of diesel-electric submarine by a factor of 3 to 5 (Section 13.2).
- The fuel cell, an electrochemical form of AIP, will provide twice the efficiency of heat engine AIP systems and will enable diesel-electric submarines to operate as quietly as they do on battery power (Section 13.2).
- With any form of AIP, diesel-electric submarines will not be capable of the sustained speeds of nuclear-powered submarines (Section 13.2).
- Diesel reforming (producing hydrogen from diesel fuel) has to be developed for fuel cells to be technically and economically acceptable for marine use (Section 13.2).
- An integrated power system (IPS) with electric drive will morph into the all-electric ship (AES) and then into the electrically reconfigurable ship (ERS); expected operational benefits are fewer prime movers, less maintenance, fuel savings, reduced manning, power continuity to fight the ship, and future weapon technology insertion in an open system architecture (Section 13.2).
- Automating fire protection and fluid system management will enhance ship survivability and reduce manning (Section 13.3).
- The stealth contest will continue as the drive to operate stealthy submarines competes with the drive to detect them (Section 13.4).
- Electric remotely operated vehicles (ROVs) will be lighter, more efficient, less expensive, and easier to maintain, and they will require much lighter umbilical cables, all of which reduces workload of support ship equipment (Section 13.4).
- The value of the unmanned underwater vehicle (UUV) for the mine countermeasure (MCM) mission will be realized by the increased search area coverage by networked UUVs (Section 13.4).
- Manning is the dominant cost driver in operating and supporting ships during their lifetime; system design focus on abilities in which humans surpass machines and vice versa can lead to significant manning reductions (Section 13.6).

OVERVIEW

This section covers six groups of marine systems technologies: Ocean Salvage, Propulsion, Signature Control and Survivability, Undersea Vehicles, Advanced Hull Forms, and Human Engineering.

Section 13.1, Ocean Salvage, covers systems for locating and recovering sunken vessels and other objects on the ocean floor. Since crashed aircraft are the most frequent objects of salvage activity, the discussion focuses on systems used in search and recovery operations. Many of the relevant technologies are related to subsystems of ROVs. ROVs and their subsystems—search sensors, navigation and positioning, communications, energy, propulsion, and robotic manipulators—are also covered in Sections 13.2 and 13.4.

Section 13.2, Propulsion, covers technologies that enhance performance—speed, range, endurance—and survivability of surface and subsurface vessels by improving propulsive efficiency and quietness of propulsion systems. These systems include power plants, drive systems, and propulsors. Among thermal power plants, the intercooled recuperated gas turbine and closed-cycle engines are the principal items of interest. The closed-cycle engines are AIP systems, which improve the range and endurance of conventional diesel-electric submarines. Electrochemical power sources include fuel cells and batteries, both of which are also covered in Section 7. Propulsors include single- and multiple-component subcavitating propellers, high-speed propellers, and waterjets.

Section 13.3, Signature Control and Survivability, identifies and discusses the types of signatures—acoustic, infrared, radar, magnetic, visual, wake, and other electromagnetic—that are important in the surface and subsurface marine environment. This subsection supplements Section 18, which broadly covers signature control for air, land, and sea systems. Signatures and signature control are also important factors in discussions of propulsion systems in Section 13.2 and of undersea vehicles in Section 13.4.

Section 13.4, Undersea Vehicle, covers the following technology areas related to submarines: stealth, architecture, sensors and connectivity, payload, and power density. This subsection also covers deep submersible vehicles (DSVs), ROVs, and UUVs. The discussion of these submersible vehicles focuses on their subsystems: energy, propulsion, materials and structures, navigation and positioning, guidance and control, data processing, communications, work systems (robotic manipulators), acoustic and optical sensors, and launch and recovery. Technology transfer from other industries and technical fields is identified for submersible vehicle subsystems. Current capabilities of submersible vehicles to perform several functions are described in general terms (good, limited, poor). The MCM mission gets special attention because of the proliferation of sea mines among Third World countries and the increased threat of conflict in littoral areas.

Section 13.5, Advanced Hull Forms, covers unconventional hull designs that generally offer greater speed and stability than conventional monohulls, which are by far the most widely used hull forms. This subsection describes these unconventional hull forms: air cushion vehicle (ACV), surface effect ship (SES) hydrofoil, multihull vessels (catamaran and trimaran), small waterplane area twin hull (SWATH) ships, and hybrids.

Section 13.6, Human Systems Integration, identifies a vital part of total system design in the human-centered environment of surface ships and submarines. The major ownership cost of ships is incurred in their lifetime operations and support. The dominant cost driver is manning. Reducing manning requires detailed examinations of the man-machine requirements for operating, maintaining, fighting, and saving the ship. This subsection discusses using superior (to machines) human abilities, which, with machines and software doing what they do better than humans, combine to enhance overall system performance with fewer people.

SECTION 13.1—OCEAN SALVAGE

Highlights

- Aircraft are the most frequent objects of ocean salvage.
- Human physiological limits and improving capabilities of submersible vehicles will continue to limit employment of divers to depths of about 150 ft.
- Ocean search and recovery technologies include ROVs and their subsystems. ROV subsystems—energy, material and structures, guidance and control, navigation and positioning, communications, and manipulators—covered in Section 13.4, Undersea Vehicles, are expected to experience evolutionary improvement.
- A new generation of electric ROVs, covered in Section 13.2, Propulsion, will (1) have increased power density, (2) be lighter and less expensive, (3) require less maintenance, and (4) need a much lighter umbilical cable.

OVERVIEW

Navy salvage missions have long included sea line of communications (SLOC) control (towing and debeaching), amphibious support (debeaching and underwater repair), battle damage repair (towing, firefighting, and damage control), and harbor clearance (damage control, heavy lift, and demolition). Another salvage mission, deep ocean operations ("deep ocean" refers to depths below about 150 ft, a depth at which bottom time limitations make the use of divers problematic), has been formulated by the confluence of several technological advances: manned and unmanned submersibles replaced man divers; sonar and computer advances provide efficient and reliable acoustic search systems; and dynamic vehicle positioning can be done with such accuracy that mooring is not required.

Technologies in this section are used by both military and civilian communities to recover sunken vessels and aircraft and to implant equipment on the ocean floor.

Vessels are sometimes sunk as a result of collisions, explosions, or other maritime disasters. Whether such vessels can be salvaged depends on several considerations: the sea conditions, the current, the depth, equipment available, estimated cost. The lift needed to bring a sunken vessel to the surface is provided by several means: heavy lift ships, floating cranes, pontoons, compressed air, foam, trained divers, and submersible vehicles. Underwater work on a sunken ship, done by divers or submersible vehicles, consists of connecting air lines to the ship's fittings, securing lifting cranes or wire rope hawsers, and encircling the vessel's hull with lifting hawsers. Figure 13.1-1 illustrates the use of heavy lift craft and wire cables to raise sunken vessels. This technique was used to clear wreckage in the Suez Canal in 1974. The amount of lift that can be applied, either by lifting hawsers or compressed air pumped into a ship, is limited by the size of the sunken vessel. Foam, similar to the synthetic foam used to construct submersible vehicles, provides underwater buoyancy; the foam is used to displace flood water in situations where the ship's envelope cannot be sealed adequately to restore lost buoyancy by pumping in compressed air. This technique is illustrated in Figure 13.1-2.

While the figures depict salvage operations for ships, aircraft are the more frequent objects of ocean salvage. Most salvage operations for military aircraft get little public attention. Search and recovery of crashed airliners and small aircraft with famous occupants are widely covered by the media. In the last few years salvage objects included TWA 800 (July 1996), John Denver (October 1997), Swiss Air III (May 1998), John Kennedy, Jr. (July 1999), Egypt Air 990 (October 1999), and Alaska Air 261 (February 2000). Salvage of ships or aircraft involve two phases of operations, search and recovery, which are described by the Navy in its ship salvage manual (U.S. Navy, 1993).

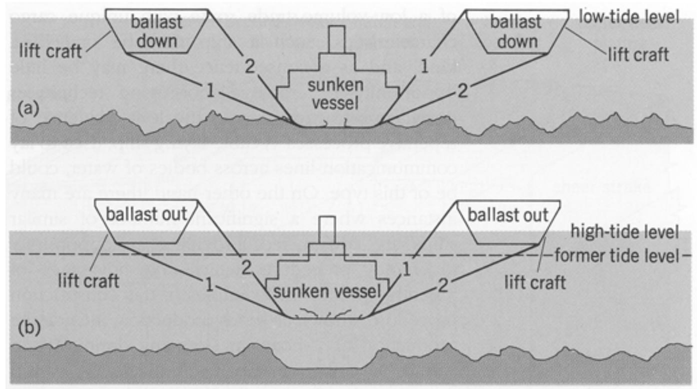

Figure 13.1-1. Lift Craft Operation: (a) At low tide, the lift craft are ballasted down, and cables are passed beneath the sunken vessel and pulled tight. (b) At high tide, the lift craft are deballasted, and the sunken vessel is raised above the ocean bottom and towed away. (Source: McGraw-Hill, 1997)

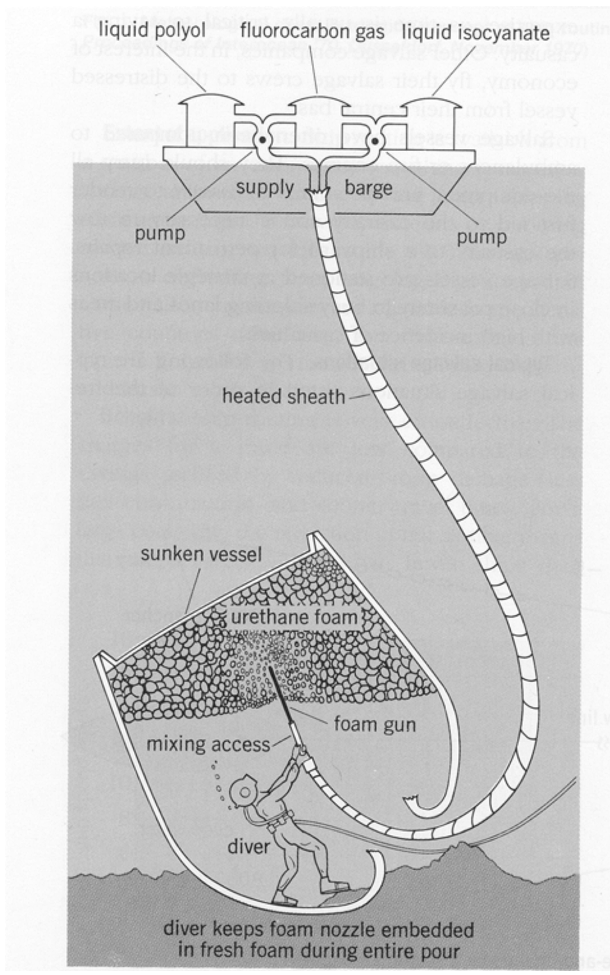

Figure 13.1-2. Diver Placing Urethane Foam in a Sunken Vessel. The hardened foam displaces water to make the vessel buoyant. (Source: McGraw-Hill, 1997)

A. SEARCH

The predominant search tools are identified below:

Echo Sounder is a sonar that produces continuous seafloor topography data, which are critical to avoid loss or damage of towed side-scan sonar or a pinger-locator. Poor resolution and narrow swath coverage limit objects of interest to large shipwrecks. This sonar is not useful for searching for aircraft debris fields.

Side-scan sonar, the primary search sensor, produces a plan view image of the seafloor. The resulting acoustic image reveals man-made objects and topographic and compositional (rock/mud/sand) features of the seafloor. A side-scan sonar system has three basic components: (1) towfish that houses the transducers and associated electronics, (2) the electromechanical tow cable that connects the towfish to the shipboard control and display electronics, and (3) the shipboard unit that controls the operation of the towfish and displays/records the sonar image for interpretation by the operator. A single pass swath of 50 m to more than 2,000 m makes the side-scan sonar a very efficient (rate of area searched per unit time) search tool. Searching for a small object such as a 55-gallon drum would involve a narrow 50-m to 100-m swath with a high-frequency (500 kHz) system. Larger objects such as shipwrecks would involve low frequency (30 kHz) systems with swath coverage up to 5 km (U.S. Navy, 1993). Figure 13.1-3 shows the Orion Search System, a digital side scan sonar that has 50 kHz side-looking transducers on both sides for long-range detection of objects and dual 250-kHz side-looking transducers for high-resolution passes over items of interest (U.S. Navy Supervisor of Salvage and Diving, 1999).

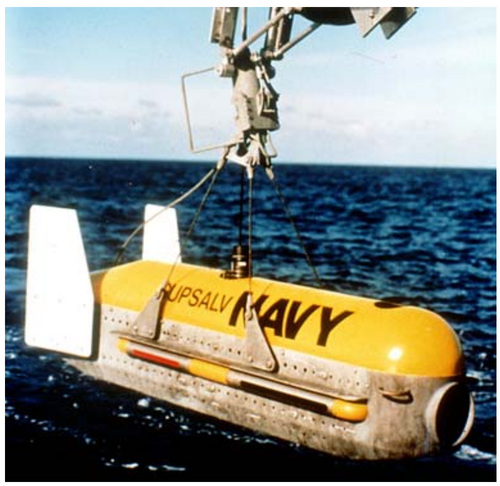

Figure 13.1-3. Orion Search System (Source: U.S. Navy Supervisor of Salvage and Diving)

A *pinger-locator* (Figure 13.1-4) is a passive acoustic system that listens for 37-kHz signals from cockpit voice recorders and flight data recorders to locate aircraft that have crashed at sea. Figure 13.1-5 shows the little over 5 ft long towed pinger locator (TPL) without fins.

A *magnetometer* searches for metal objects that are magnetized. It is a secondary sensor useful in target-rich situations in which sonar cannot distinguish between metallic and nonmetallic returns. It is especially useful for locating objects buried in bottom sediment.

An *optical imaging system* can identify an object without the time-consuming contact classification. The actual sensing devices include still photographic cameras, real-time video cameras, electronic still cameras, and laser imagers. The cameras need conventional strobe or floodlights for illumination. Because of underwater attenuation of light and backscattering, the cameras need to be within 10 to 20 m of an object to make identification. The attenuation and backscattering are less severe for laser imaging systems, which can image objects to distances of about 50 m.

An *ROV* is an unmanned submersible that carries sensors and maneuvers them in proximity of search objects. The ROV uses outboard acoustic and optical sensors to locate objects, confirm their identification, and perform recovery tasks. Figure 13.1-6 shows the Navy’s Deep Drone 7200, an 8,000-ft-depth-rated ROV, which is designed

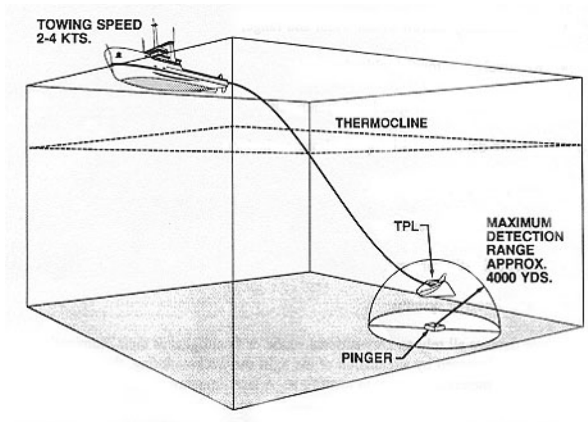

Figure 13.1-4. TPL Operation. (Source: U.S. Navy Ship Salvage Manual, Vol. 4)

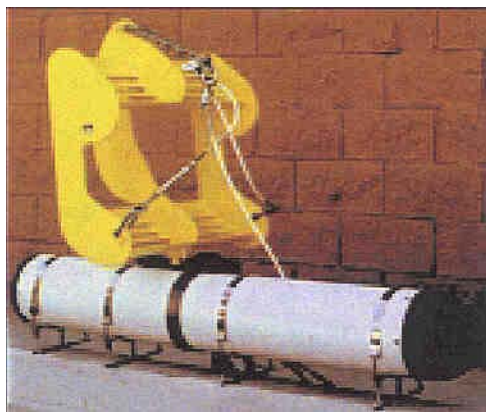

Figure 13.1-5. Towed Pinger Locator 30 (TPL-30)
(Source: U.S. Navy Supervisor of Salvage and Diving, 1999)

Figure 13.1-6. Deep Drone 7200, an 8,000-ft Depth ROV
(Source: U.S. Navy Supervisor of Salvage and Diving)

for deep ocean recovery. Figure 13.1-7 shows a 1,000-ft-depth-rated mini-ROV which the Navy uses for shallow water surveys, photographic documentation, and light salvage/recovery.

Figure 13.1-7. Mini-ROV MR-1
(Source: U.S. Navy Supervisor of Salvage and Diving)

A navigation system provides these basic functions: (1) steers the search vessel along predetermined tracks; (2) tracks the position of the search vessel and the sensor towfish; and (3) returns to any position at a later time. The Global Positioning System (GPS) is used to track the surface vessel; acoustic positioning, such as shown in Figure 13.1-8, tracks subsurface positions of the search sensor.

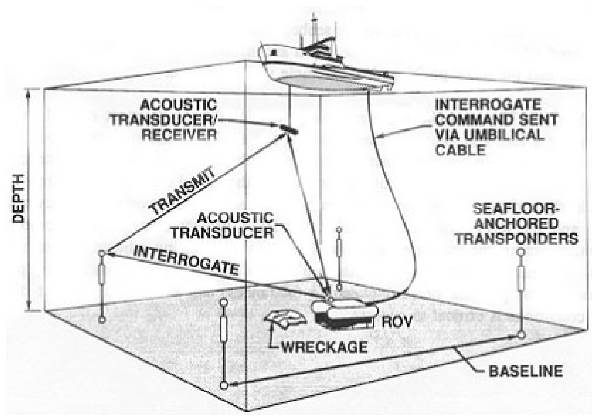

Figure 13.1-8. Positioning ROV by a Long-baseline System.
(Source: U.S. Navy Ship Salvage Manual, Vol. 4)

B. RECOVERY

Recovery systems include divers, manned submersibles, and ROVs. Several factors are considered by the Navy in selecting a system for a recovery operation:

> [The] task to be accomplished, existing technology, availability, operational feasibility, and economics. Every time an individual submerges, regardless of depth, the degree of danger within the operation increases… As depth increases so does the size, cost, and technical sophistication of the physical plant that supports the diving operation. There is also a decrease in the productivity of divers and in the proportion of productive time in each dive… Divers are most effectively employed in shallow water when the hazards of the operation and the decompression debt are limited (U.S. Navy, 1993).

Divers have advantages of human vision, judgment, and manipulative skills. But diving operations beyond shallow water require "numerous divers and topside support personnel" plus "recompression chambers, compressors, gas banks, and associated equipment."

Manned submersibles take man deeper than divers and avoid the decompression debt. These vehicles are especially useful in enabling an operator to view a target in three dimensions and to analyze the seafloor situation.

Manned submersibles operate without tethers; they thus avoid maneuverability limits due to drag on the umbilical resulting from high currents.

ROVs are equipped with thrusters, acoustic and/or optical imaging devices, and manipulators for work. They are controlled through an umbilical. ROVs are the Navy's tools of choice for most deep ocean salvage operations. They are available in a broad range of capabilities, allowing the equipment to be fitted to the task. "Unmanned ROVs eliminate the risk to human life inherent in manned systems. An ROV is capable of operating at depth until the task is complete or maintenance is required; operator fatigue does not limit mission duration. Long mission duration is particularly advantageous where the depth requires long ascent and decent times" (U.S. Navy, 1993).

Recovery operations involve lifting objects from the sea floor. Lifts can be accomplished by (1) an ROV attaching a gripping device, which is attached to the ROV frame, to the object; (2) buoyant lift, as illustrated by Figure 13.1-2; and (3) synthetic line lift, as illustrated by Figure 13.1-1. Recovery of objects is sometimes time critical—before an adversary can intervene or make the recovery himself.

C. WORK SYSTEMS

Work systems (i.e., manipulators) are critical technology items for which significant developmental improvement is expected. Manipulators are used by DSVs and ROVs to accomplish military, industrial, and scientific tasks. Figure 13.1-9 shows the Navy's cable-controlled underwater recovery vehicle (CURV), which is designed for deep water recovery at depths up to 20,000 ft; a robotic manipulator can be seen forward on the port side of the CURV platform. Manipulator use on autonomous underwater vehicles (AUVs) is embryonic, and much R&D is needed before AUVs are able to perform more than simple tasks. The National Research Council's Marine Board (Marine Board, 1996) described current manipulator use and new control techniques as follows:

> Current practice involves rate or master-slave manipulators, where the operator (located inside a DSV or on a surface vessel controlling an ROV) operates the arm by throwing switches or by moving a miniature version (the "master") of the manipulator on the vehicle (the "slave"). Typically, modern hydraulic arms on large ROVs can lift hundreds of kilograms, even when fully extended.
>
> New control techniques drawn from space developments will allow the human operator to command directly at the task level what is to be done with the object of interest, and the vehicle-manipulator system will respond by carrying out that command. The operator needs no special "crane operator" skills, and a scientist or the field engineer can play the operator role. The operator can then focus completely, in real time, on the task itself and the objects to be manipulated (p. 36).

Figure 13.1-9. The CURV Being Hoisted Aboard the USS Grasp After Making a Dive to 350 ft (Source: U.S. Navy)

Manipulators use "end-effectors" to perform actual tasks. These end-effector devices are general-purpose hands or grippers, special-purpose power tools (drills, cutters), or wrenches (for offshore oil work, for example). The development of new underwater sensors for proximity, force, touch, and audio would give the operator feedback on the performance of manipulators and other mechanical systems. These developments will likely be based on devices for terrestrial and space applications.

Figures 13.1-10 and 13.1-11 show the Navy's ROV Deep Drone using a robotic manipulator to recover small pieces of wreckage during search and recovery operations at the TWA 800 crash site.

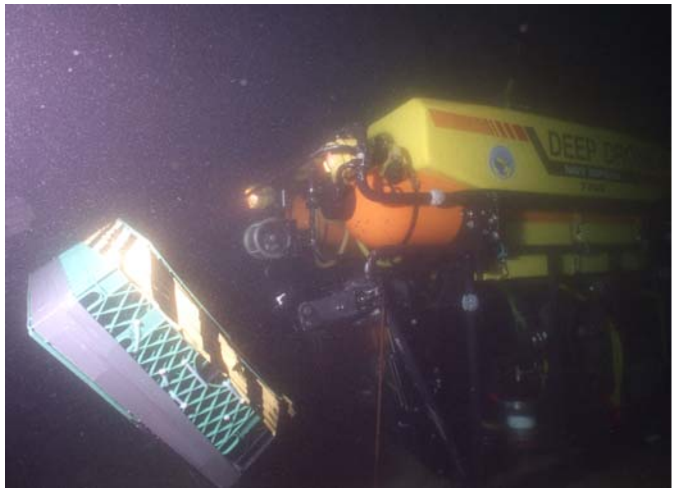

Figure 13.1-10. ROV Deep Drone Using Robotic Manipulator to Recover Wreckage Debris at TWA Flight 800 Crash Site (Source: U.S. Navy)

Figure 13.1-11. Another View of ROV Deep Drone Using Robotic Manipulator at TWA Flight 800 Crash Site (Source: U.S. Navy)

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SECTION 13.2—PROPULSION

Highlights

- The intercooled recuperated gas turbine (ICRGT) will provide a 30-percent improvement in fuel efficiency over a simple-cycle gas turbine of the same power level.
- With AIP, diesel-electric submarines submerged endurance will be extended by 3× to 5×; they will not have to snorkel as frequently to recharge batteries.
- The fuel cell, an electrochemical form of AIP, will provide twice the efficiency of heat engine AIP systems and will enable diesel-electric submarines to operate as quietly as they do on battery power. They can extend the battery-only submerged range by a factor of 5. Fuel cells are reliable, long-life options for auxiliary propulsion. Because their power density is half that of gas turbines, they are not useful for surface ship main propulsion in the near term.
- With any form of AIP, diesel-electric submarines will not have the capability for sustained speeds of nuclear-powered submarines in the near term. The long-term outlook is uncertain but has potential.
- Diesel reforming (production of hydrogen from on-board diesel fuel) has to be developed for fuel cells to be technically and economically acceptable for marine use.
- Electric drive (ED) in an IPS architecture will apportion electric power flexibly for propulsion, ship service, and combat systems for many types of ships. Fewer prime movers will be needed, which means fuel savings of more than 15 percent for many gas turbine combatants and reduced maintenance. By electrification of auxiliary systems now powered by steam, hydraulics, or compressed air, IPS with ED will evolve into the AES, in which automation will reduce manning. With further development, the AES will evolve into the ERS, which will accommodate future direct energy conversion sources and electric weapons, sensors, and defenses. The ERS will also be able to maintain power continuity to undamaged combat systems if the ship takes a hit.

OVERVIEW

Marine propulsion systems include (1) power plants, which provide power to propel vessels; (2) drive systems, which transmit power to propulsors; and (3) propulsors, which convert power to thrust. The major types of power plants are thermal engines, nuclear reactors, closed-cycle and semi-closed-cycle thermal engines, and electrochemical power sources (Simmons et al., 1991).[1]

A. POWER PLANTS

Power plants include thermal power plants, nuclear reactors, closed- and semi-closed-cycle thermal engines, and electrochemical power sources.

1. Thermal

a. Steam

These large, heavy power plants, which are efficient at cruise speed, are being supplanted by diesels and gas turbines.

[1] The sources of much of the material in this subsection are identified by the list of references.

b. Nuclear Steam

The range advantage of these systems is outweighed by radiation hazards, shielding requirements, high cost, and end-of-life disposal.

c. Diesels

Diesels are efficient at all loads, but power output is limited, and they are noisy.

d. Gas Turbine (Simple Cycle)

These lightweight, compact engines require a large volume of air and have low efficiency at partial power.

e. Intercooled Recuperated (ICR) Gas Turbine (ICRGT)

The high cost of ICR engines will be outweighed by high operating efficiency at all loads and by an expected 30-percent fuel savings compared with current naval engines. ICR design is focused on maintainability and low support cost (NAVSEA 03R2, 1994). Figure 13.2-1 shows a schematic comparison of a simple-cycle gas turbine and an ICR cycle engine. The intercooler increases the air density by rejecting heat between the intermediate-pressure compressor (IPC) and the high-pressure compressor (HPC). The exhaust heat recuperator preheats air leaving the HPC before combustion. Figure 13.2-2 shows the effect of recuperation on simple-cycle efficiency. Recuperation could add 13 points of efficiency, for example, for a simple-cycle gas turbine engine operating at a 6:1 pressure ratio and a turbine inlet temperature of 1,800 °F. Figure 13.2-3 shows the increased brake horsepower that recuperation provides in the WR-21 ICRGT that is being developed for the Navy. Figure 13.2-4 shows the effect of recuperation and intercooling. Figure 13.2-5 shows the estimated annual fuel savings that the WR-21 intercooling and recuperation will provide.

The Ship Support Agency (SSA) of the UK Ministry of Defense assessed the relative merits of three prime mover categories—diesel, simple-cycle gas turbine (SCGT), and ICRGT—over the period 1995–2020 in terms of efficiency, complexity, and cost of ownership. The assessment was made for a “blue-water” navy, not a “brown water” navy for which the arguments could be different. The SSA assessment says that:

- The efficiency of diesels and ICRGTs will be essentially the same in the future and much better than SCGTs.
- With respect to complexity, diesel complexity has increased by the addition of water injection, timing control, and exhaust treatment necessary to meet emission control standards. Gas turbines are basically more complex than diesels, and they “have become more so through the introduction (for efficiency reasons) of recuperation and intercooling.” But there will be no increase in complexity attributable to emission legislation since “exhaust emission is among other things a function of peak cycle temperature, the threshold for which lies at the current operating temperature of gas turbines.” Thus, complexity will not be a discriminator.
- Cost of ownership favors gas turbine-powered vessels over diesel vessels, which “will need more looking after (requiring extra crew), and will be more expensive to buy.” Because “they are too big to remove, diesels have to be overhauled in place [with] the host vessel remaining docked for as long as 2 months compared to 2 days for a gas-turbine-powered vessel” (Pengelley, 1999). The latter can be hoisted from the vessel and replaced with another gas turbine. Diesel overhaul could be accomplished by removing one cylinder at a time, but a diesel-powered vessel operating on N-1 cylinders would be more noisy.

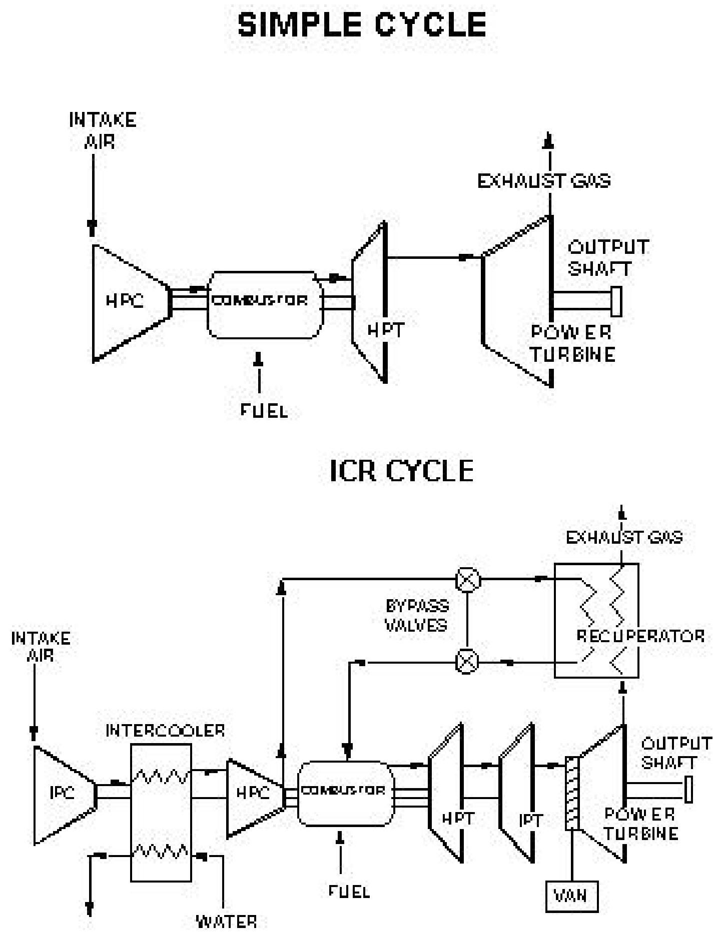

Figure 13.2-1. Simple and ICR Cycle Schematics (Source: Northrup Grumman Marine Systems)

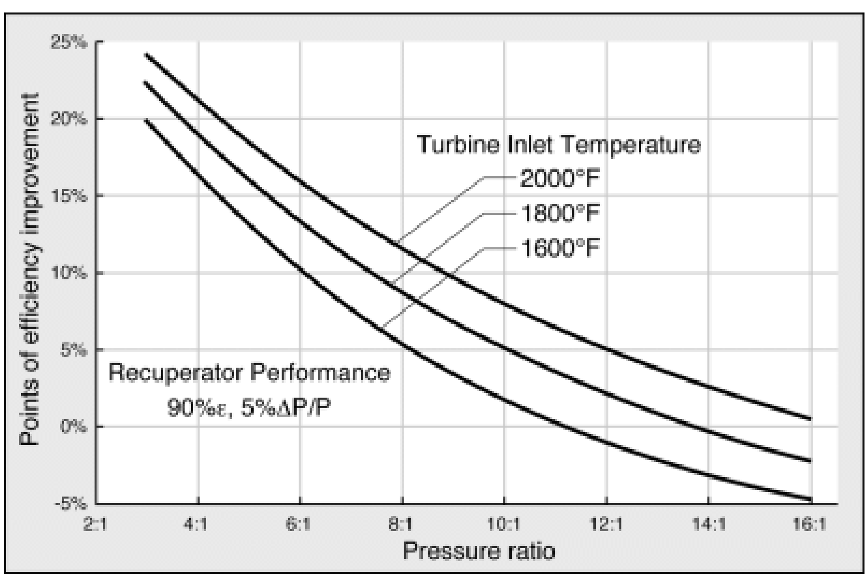

Figure 13.2-2. Effect of Recuperation on Simple-Cycle Efficiency (Source: Northern Research and Engineering Corporation)

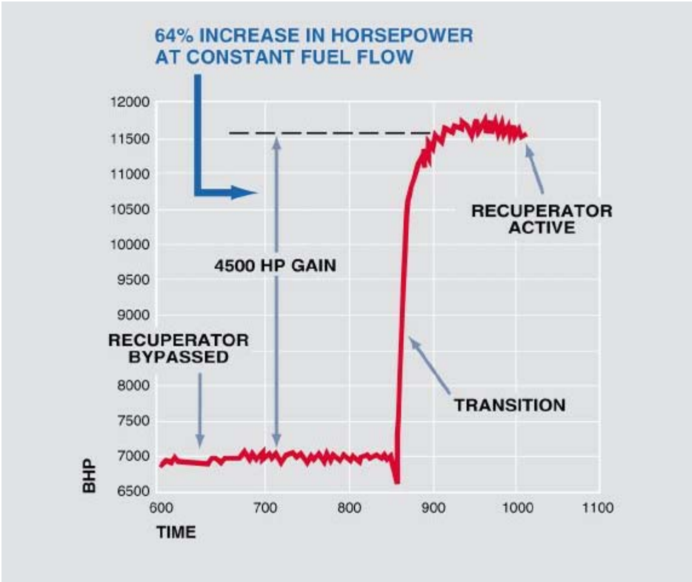

Figure 13.2-3. Advanced Cycle Performance with WR-21
(Source: Northrup Grumman Marine Systems)

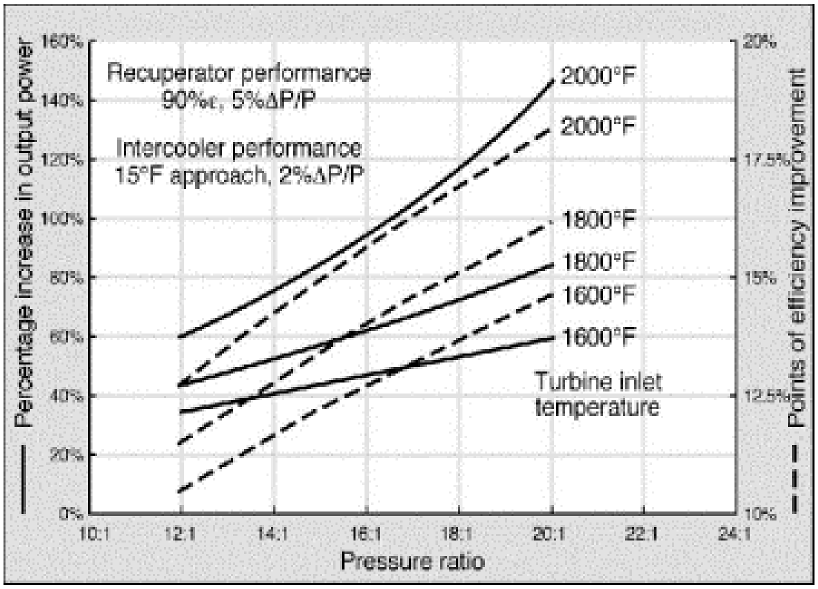

Figure 13.2-4. Effect of Recuperation and Intercooling
(Source: Northern Research and Engineering Corporation)

f. Hybrids

Power plant arrangements have included: (1) paired combinations of basic engine types as part of a single-propulsion system or (2) two different propulsors. These “hybrid” power plants exploit the advantages of each basic engine type and thereby improve their overall power generating capability. Combined systems are particularly useful for powering ships during long periods of cruising at comparatively low speed and low power, while having sufficient reserve power to operate at high speed for a short period. The typical combined installation incorporates one or more small, fuel-efficient engines for cruising and a high-power engine plant that can provide additional

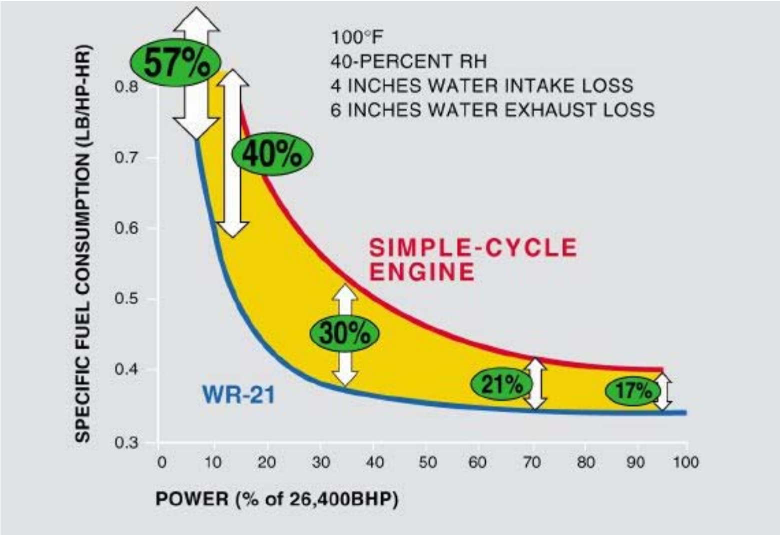

Figure 13.2-5. 27–30-percent Annual Fuel Savings with WR-21
(Source: Northrop Grumman Marine Systems)

energy needed for high-speed operation. As a result, combined plants can be much more efficient than power plants with a single type of engine (Simmons et al., 1991). Table 13.2-1 identifies various hybrid power plants that have been developed or proposed for naval surface vessels.

Table 13.2-1. Hybrid Power Plants for Surface Vessels
(Source: Simmons et al., 1991)

Designation*	Cruise Power	Boost Power	Recent Application	Advantages
COSAG	Steam	Gas turbine added	Royal Navy's Type 82 and *COUNTY*-class destroyers	Steam plant needs to be sized for cruise only
CONAS	Nuclear steam	Conventional steam added	Soviet *KIROV*-class battle cruiser	Nuclear plant needs to be sized for cruise only
CONAG	Nuclear steam	Gas turbine added	Proposed for aircraft carriers and cruisers	Nuclear plant needs to be sized for cruise only
CODOG	Diesel	Gas turbine only	U.S. Navy's *PEGASUS*-class Hydrofoils. Various European destroyers and frigates.	Diesels provide efficient cruise. Gas turbines provide efficient boost.
CODAS	Diesel	Conventional steam only	None	Diesel provides efficient cruise
CODAD	Diesel	Diesel added	None	Simplifies logistics since only one type engine is used
CODAG	Diesel	Gas turbine added	Range of vessels from small patrol craft to destroyers	Diesels provide efficient cruise. Lightweight gas turbine provides fast transition to boost.
CODLAG	Diesel (with electric drive)	Gas turbine added	Royal Navy's new Type 23 frigate	Diesels provide efficient cruise. Gas turbine adds efficient boost
COGOG	Gas turbine	Gas turbine (higher power) only	Royal Navy's Type 42 destroyers	Maintain fuel efficiency by using small gas turbine for cruise, larger gas turbine for boost
COGAG	Gas turbine	Gas turbine added	DD-963-class destroyers FFG-7-class frigates CG-47-class cruisers DDG-51-class destroyers	Maintain fuel efficiency by using one gas turbine per shaft for cruise, two per shaft for boost
COGAS	Gas turbine	Steam added	Proposed for DDG-51s and for refit on DD-963s	Uses heat in gas turbine exhaust to run boost steam plant, thereby increasing efficiency

* CO = combined; A = and; G = gas turbine; N = nuclear; S = steam; O = only; D = diesel; L = electric drive.

2. *Nuclear Reactor*

Table 13.2-2 describes the principal characteristics and advantages and disadvantages of various types of reactors. With few exceptions the Navy has equipped its attack and ballistic missile submarines and its aircraft carriers with pressurized water reactors (PWRs). The Navy is expected to stay with basic PWR design for the foreseeable future.

Table 13.2-2. Comparison of Nuclear Reactor Types (Source: Simmons et al., 1991)

Type	Reactor Coolant	Thermal Efficiency	Average Power Density (kW/L)	Applications	Principal Advantages	Principal Disadvantages
Pressurized Water Reactor (PWR)	Liquid H_2O	0.33	106	U.S. Naval plants; utilities	Much good experience; many proven upgrades in place	High pressure; heavy components; low efficiency
Liquid Metal Reactor (LMR)	Liquid sodium (Na), lead, bismuth	0.42	260	Soviet Naval plants[a]	High efficiency; high power density	Violent Na-H_2O reactions; Na radioactivity
High-Temperature Gas-Cooled Reactor (HTGR)	Gaseous helium	0.46	5–800	No recent plants	High efficiency; benign coolant	Poor heat transfer; very low power density
Boiling Water Reactor (BWR)	Two-phase (liquid vapor) H_2O		55	Utilities	No extra steam-generating equipment	Ship motion problems; low power density
Organic Cooled Reactor (OCR)	Organic compound (liquid)			No recent plants	Low pressure, no boiling; clean coolant	Very little operating experience

[a] U.S. experimented with Na; Soviet plants used lead, bismuth.

3. *Closed- and Semi-Closed-Cycle Thermal Engines*

Closed-cycle thermal engines recycle their working fluid and employ a heat source that does not require access to the atmosphere. A semi-closed-cycle engine does not use stored oxidizer when operating on the surface with access to the atmosphere. The principal applications of these AIP sources are in conventional submarines and other underwater vehicles. The principal AIP systems are traditional lead-acid batteries, high-performance batteries, closed-cycle diesels, Stirling engines, steam Rankine cycle engines, closed-cycle (Brayton) gas turbines, and fuel cells (nuclear reactors are also AIP systems). Fuel cells and batteries will be discussed separately. Table 13.2-3 compares heat sources for closed-cycle engines. Table 13.2-4 shows some characteristics of the most popular AIP systems.

a. *Closed-Cycle Diesel (CCD)*

Oxygen for combustion is provided from a stored source when the host vessel is submerged. The CCD is a robust, reliable engine well-suited for retrofit in conventional diesel submarines. It has the flexibility to cover a broad range of power output; hence, its potential for providing a high-speed submerged capability is limited in endurance only by a vessel’s fuel and oxygen supply. The CCD’s exhaust gases contains carbon dioxide, which can be absorbed by seawater, oxygen, and argon. Oxygen bubbles are detectable by active sonar at long distances (Windolph, 1998).

b. *Stirling*

Stirling engines use an external heat supply and helium as a working medium for combustion. A pair of these engines has been installed on each of three Gotland submarines in Sweden. They run more smoothly than CCDs, but have lower efficiency because of temperature losses associated with the external heat supply. The Stirling offers a single power rating so a couple of engines must be used in parallel to meet a higher power requirement. The Stirling is a smooth-running engine with low efficiency, and it requires special sulfur-free fuel. It has no other military or commercial application and no growth potential. Carbon dioxide/oxygen-mix bubbles in its exhaust are easily detectable by active sonar (Windolph, 1998).

Table 13.2-3. Comparison of Heat Sources for Closed-Cycle Engines (Source: Simmons et al., 1991)

Heat Source	Advantages	Theoretical Energy Density		Disadvantages
		Gravimetric (kW-hr/lb)	Volumetric (kW-hr/ft³)	
Hydrocarbon combustion	Fuels readily available	1.2–1.35	40–65	High combustion temperature, disposal of exhaust products
Hydrogen combustion	Water is only combustion product	2.04	32–34.5	Hydrogen storage, high combustion temperature
Exothermic chemical reactions	Higher energy densities	1.1–2.3	54–155	Accumulation and/or disposal of reaction products
Carbon block heat storage	No reaction products	0.50	68.5	Insulation for carbon block heated to 5,000 ° F
Nuclear reactor*	Long interval between refuelings	93	2,480	Shielding requirements
Radioactive materials (e.g., plutonium-238, strontium-90)	Long interval between refuelings	1.0	170	Shielding requirements

* Assumes 10 years of operation and average output of 200 kW.

Table 13.2-4. Characteristics of Principal AIP Systems (Sources: Windolph, 1998; Naval Forces, 1996; and Simmons et al., 1991)

Characteristic or Parameter	AIP System			
	Closed-Cycle Diesel	Stirling Engine	MESMA[a] Engine	Fuel Cell
Approximate efficiency (%)	30	30[b]	25	up to 70
Fuel	diesel	diesel	ethanol	hydrogen
Energy conversion	indirect/combustion	indirect/combustion	indirect/combustion	direct
Maximum temperature (deg C)	> 400	> 750	> 700	80
Power range (kW)	275–400	75	200	50
Oxygen consumption (kg/kW)	0.75	1.0	1.1	0.4
Main propulsion	yes	no	no	no
Auxiliary propulsion[c]	yes	yes	yes	yes
Exhaust pump required	yes	> 180 m	> 600 m	no
Cooling pump required	yes	yes	yes	no
Acoustic signature	average	average	average	very low

[a] Module d'Energie Sous-Marin Autonome—Steam Rankine cycle.

[b] Slightly less than CCD.

[c] May be used at times as sole propulsion means—at low speeds.

c. Steam Rankine Cycle

This French MESMA system is a conventional steam turbine assembly, which produces thermal energy through combustion of a gaseous mixture of ethanol and oxygen. The thermal energy is then transformed into electric energy by a conventional Rankine-cycle circuit—steam generator turbo-alternator, condenser (Annati, 1996; Robertson, 1996). This engine is being installed in the last of three Agosta 90B submarines for Pakistan with the possibility of being retrofitted in the first two. High-efficiency losses and high oxygen consumption lead to large submarines and thus larger target size. Ethanol, which has a low ignition point, is more difficult to handle on board than diesel fuel. The MESMA AIP has no chance in the future AIP market because other AIP systems are less expensive (CCD) or are more efficient and have growth potential (fuel cell) (Windolph, 1998).

d. Closed-Cycle Gas Turbine

With inert gas working fluid and a high-speed alternator, the rotating machinery is more compact than a diesel generator. That advantage is balanced by the turbine's combustion circuit and heat exchanges. Power density, efficiency, fuel storage, and liquid oxygen storage are expected to be about equal to those parameters for CCD at 400 kW but inferior at lower powers. Cost would be greater than for a CCD (Donaldson, 1996). We have not seen discussion of any use of this AIP system.

4. Electrochemical

Electrochemical sources, which are also AIP systems, include fuel cells, rechargeable batteries, and nonrechargeable batteries.

a. Fuel Cells

All fuel cells operate on the same basic principle: they generate electricity through an electrochemical process in which energy stored as fuel is converted directly into electricity. The fuel cell operates like a battery; it combines hydrogen and oxygen electrochemically to produce DC electricity. One difference: batteries do not generate water. It does not run down. It does not require recharging. Fuel cells are more efficient than diesel engines or gas turbines and may use significantly less fuel with almost no pollution. They have no moving parts. They require minimal manning. But power density of fuel cells is about one-half that of gas turbines. The DoD Fuel Cell Demonstration Program describes the operating principle and illustrates the operation (Figure 13.2-6):

> An input fuel is catalytically reacted (electrons removed from the fuel elements) in the fuel cell to create an electric current. Fuel cells consist of an electrolyte material which is sandwiched in between two thin electrodes (porous anode and cathode). The input fuel passes over the anode (and oxygen over the cathode) where it catalytically splits into ions and electrons. The electrons go through an external circuit to serve an electric load while the ions move through the electrolyte toward the oppositely charged electrode. At the electrode, ions combine to create by-products, primarily water and CO_2. Depending on the input fuel and electrolyte, different chemical reactions will occur (Web site: http://www.dodfuelcell/fcdescriptions.html).

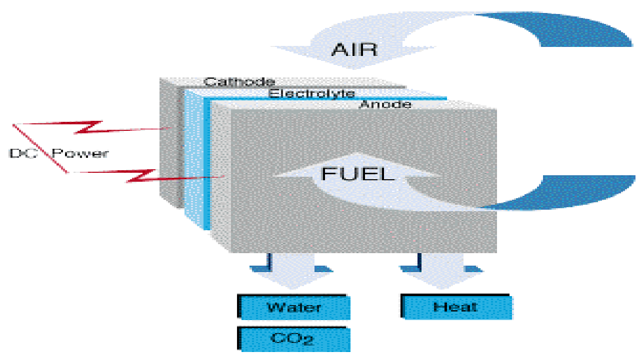

Figure 13.2-6. Fuel Cell Operating Principle
(Source: DoD Fuel Cell Demonstration Program Web site)

Fuel cells typically have three sections: fuel processor, power section, and power conditioner (see Figure 13.2-7). The functions of the sections are described below by the DoD Fuel Cell Demonstration Program:

> In the fuel processor, a fuel such as natural gas is reformed to boost the concentration of hydrogen. The hydrogen-rich fuel and oxygen (air) then feeds into the power section to produce DC electricity and reusable heat. The power section includes a fuel cell stack, which is a series of electrode plates interconnected to produce a set quantity of electrical power. The output DC electricity is then converted to AC electricity in the power conditioning section where it also reduces voltage spikes and harmonic distortions (Web site: http://www.dodfuelcell/fcdescriptions.html).

The following primary types of fuel cells are based on the electrolyte employed. These are described in a 1998 *Naval Engineers Journal* (Allen, 1998):

- *Phosphoric Acid (PA)*—Phosphoric acid cells are already commercially producing land-based electric power in premium power applications such as hospitals, a landfill, and many defense installations. These moderate temperature (210 °C) cells are suitable for applications where reliability and "clean" power is needed.

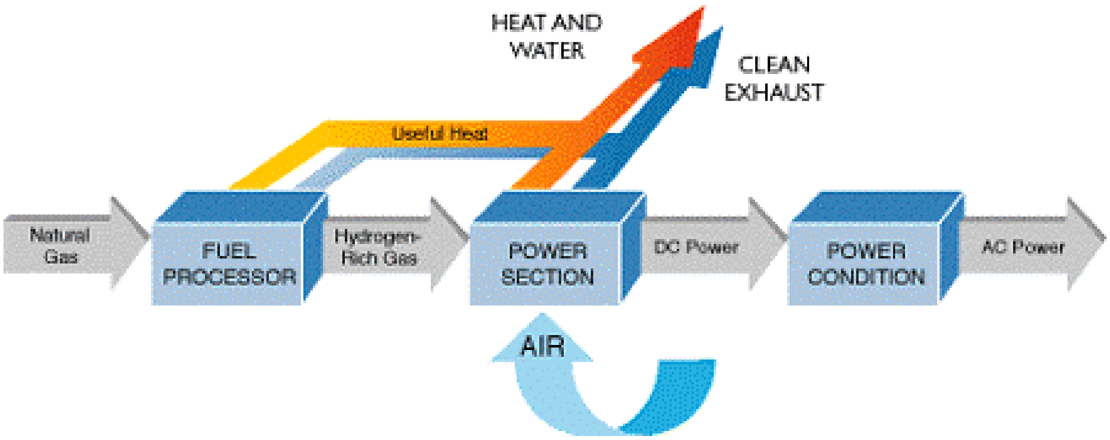

Figure 13.2-7. Block Diagram of Fuel Cell Operation (Source: DoD Fuel Cell Demonstration Program Web site)

- *Molten Carbonate (MC)*—MC fuel cells have the advantage of high system efficiencies (over 40 percent) and the ability to internally reform hydrogen-rich gases directly into hydrogen using the high temperature (1,200 °F) of the fuel cell itself. Several MC stacks have been demonstrated for electric power generation at the megawatt level. This technology has promise for marine applications, and laboratory prototypes of MC fuel cells which use a diesel-like fuel have been demonstrated.
- *Solid Oxide (SO)*—The solid oxide fuel cell (SO fuel cells are either planar or tubular in design) is based on a ceramic electrolyte and can operate at very high temperatures (1,800 °F). As a result of this high temperature, system efficiencies could potentially reach as high as 60 percent. Several kilowatt-level demonstrations of SO technology are in the works, and this cell may ultimately be applied in the marine environment.
- *Proton Exchange Membrane (PEM)*—Low-temperature (200 °F), lightweight, mostly polymer construction. These are being extensively developed for automotive applications, where rapid load change is experienced. The PEM is most promising for submarines (p. 94).

A fifth type of fuel cell, alkaline, is very expensive, but its high efficiency (70 percent) makes it attractive for space applications. Russia is reportedly using alkaline fuel cells for submarines. The alkaline fuel cell has a low temperature, but cannot use fuels containing carbon (Allen, 1998). Table 13.2-5 compares some principal characteristics of the four types of fuel cells.

Table 13.2-5. Comparison of Fuel Cell Types (Source: DoD Fuel Cell Demonstration Program Web site)

	PAFC	MCFC	SOFC	PEMFC
Electrolyte	Phosphoric Acid	Molten Carbonate Salt	Ceramic	Polymer
Operating temperature	375 °F (190 °C)	1,200 °F (650 °C)	1,830 °F (1,000 °C)	175 °F (80 °C)
Fuels	Hydrogen (H_2) Reformate	H_2/CO Reformate	$H_2/CO_2/CH_4$ Reformate	H_2 Reformate
Reforming	External	External/Internal	External/Internal	External
Oxidant	O_2/Air	CO_2/O_2/Air	O_2/Air	O_2/Air
Efficiency (HHV)	40–50%	50–60%	45–55%	40–50%

With the aid of PEM fuel cells, the submerged range of a submarine can be extended about five times battery-only range (Sattler, 1999). Due to their system-level efficiency, the use of fuel cells can reduce fuel consumed up to 50 percent over internal combustion engines and simple gas turbines (Allen, 1998). Reduced pollutants due to low nitrogen oxide (NOx) emissions are another major benefit from the use of fuel cells, as shown in Figure 13.2-8.

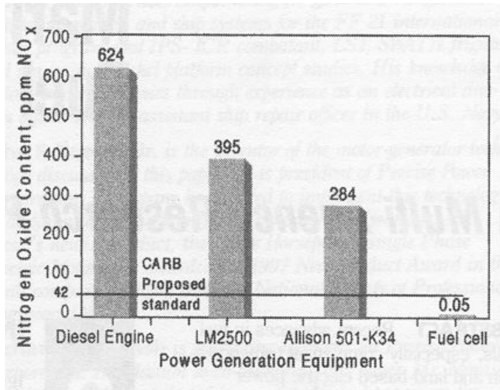

Figure 13.2-8. Nitrogen Oxide Emissions
(Source: California Air Resources Board (from Allen, 1998))

Advances in fuel cells for commercial transportation and land-based electric power generation make fuel cells an attractive source for shipboard power. Naval vessels need an affordable fuel cell power system that operates on naval logistics fuel. The challenge of developing fuel cells for shipboard power is described in Allen (1998):

> Fuel cells operate on hydrogen fuel. Any hydrogen rich material can be a source of fuel. Natural gas, methanol, and petroleum distillates as well as renewable fuels are among the leading candidates. Hydrogen is obtained by "reforming" these hydrocarbon gases and liquids. The technology for processing natural gas and methane is well developed and most commercially available fuel cells operate on these gases.
>
> However, a major obstacle to acceptance by ship operators of fuel cell technology is the fact that almost all marine vessels operate on diesel fuel (and operators are reluctant to add a second fuel system). The naval and marine infrastructure for refining, distribution, and storage of diesel fuel is unlikely to change in the near future, so fuel-processing technology must be developed before fuel cells gain acceptance for marine applications (p. 95).

Reactant Storage. Liquid oxygen cryogenically stored in shockproof tanks is used on board Sweden's Gotland and will be used on board Germany's U212/A submarines. The German developer, HDW, found metal hydride storage to be the safest method for storing hydrogen for the amount of energy needed for the U212/A. Metal hydride accumulators are arranged around the submarine's pressure hull. The hydrogen is stored at sea temperature and at low pressure for an indefinite period of time (Windolph, 1998).

Diesel Reforming. Diesel reforming is a process in which a vaporized mixture of methanol and water superheated at 250–350 °C under pressure has produced a synthesis gas consisting of about 75-percent H_2 and 25-percent CO_2. Diesel reforming requires a much higher temperature, 700–850 °C, which means much more input energy. And because commercial diesel fuel is polluted by sulfur and other impurities, a complex purification process is required to filter out the impurities before the actual reforming process. This filtering process further reduces the efficiency of the entire marine fuel-cell energy generation system (Windolph, 1998).

Given successful development of diesel fuel reforming, fuel cells will be excellent sources of power for surface ships and conventional submarines. Their inherent efficiency is above 60 percent. Their energy generation process is absolutely silent, which allows silent-mode operation that would normally be possible only with a battery system. The fuel cell can operate at any depth. Its operational and control features are very user friendly. And the fuel cell is a reliable power source with a long lifetime (Windolph, 1998). See Section 7 for more information on fuel cells.

b. Rechargeable Batteries

Table 13.2-6 shows performance characteristics of secondary (rechargeable) batteries as well as other available energy sources. In a study of technology for the Navy and Marine Corps out to 2035, the Naval Studies Board of the National Research Council presented performance data on current and advanced battery systems (Table 13.2-7). Table 13.2-8 shows energy densities of high-energy batteries considered by Germany for its first U212 submarines.

Table 13.2-6. Performance Characteristics of Available Energy Sources (Source: Marine Board, 1996)

	ASSESSMENT OF ENERGY TECHNOLOGIES FOR USVs					
Technology	**Specific Energy Wh/Kg**	**Energy Density Wh/Liter**	**Cycle Life**	**Cost $/kWh**	**Maturity for Undersea Vehicles**	**Safety Concerns**
SECONDARY BATTERIES*						
Lead Acid (Pb/Pb0)	35	90	800	50	Proven	H generation
Nickel Cadmium (NiCd)	55	130	1,000	1,500	Proven	Cd toxicity
Nickel Hydride (NiH_2)	60	150	10,000	2,000	Proven	High pressure H
Nickel Metal Hydride (NiMH)	70	175	300	50	Proven	High pressure venting
Silver Zinc (Ag-Zn)	140	380	20	1,000	Proven	H generation
Silver Iron (Ag-Fe)	150	200	200+	500–800	Demo	H generation
Li-Solid Polymer Electrolyte (LiSPE)	150	360	200	100–1,000	Lab	Lithium fire
Lithium Ion Solid State (Li-Ion-ÍPE)	150	360	1,000	100–1,000	Lab	None
Lithium Ion (Li-Ion)	200	200	2,000	500–1,000	Proven	Venting
Lithium Cobalt Dioxide ($LiCoO_2$)	220	300	50	1,000	Lab	Pressure venting, Li fire
PRIMARY BATTERIES*						
Lithium Sulfur Oxide ($LiSO_2$)	140	500	1	400	Demo	Li fire
Silver Zinc (Ag-Zn)	220	400	5	3,000	Demo	H generation
Lithium Manganese Dioxide ($LiMnO_2$)	400	450	1	200	Proven	Li fire
Aluminum-Seawater	450	400	1	100	Demo	N/A
Lithium Thionyl Chloride ($LiSoCl_2$)	480	500	1	300	Demo	Thermal runaway
Lithium Carbon Monofluoride ($Li(CF)_x$)	800	1,200	1	1,700	Proven	Li fire
FUEL CELLS						
Alkaline	100	90	400	5,000	Demo	Gaseous H and O fires
Proton Exchange Membrane (PEM/GOX/GH)	225	200	50	10,000	Demo	Gas H and O fire
Proton Exchange Membrane (PEM/LOX/LH)	450	400	50	15,000	Lab	H and O fires
Proton Exchange Membrane (PEM/SOX/SH)	1,000	883	50	5,000	Lab	N/A
Aluminum-Water Semi-cell ($Al/H_2O/LOX$)	1,200	800	1	10,000	Demo	H and O fire
HEAT ENGINES (Closed-Cycle Air Independent Propulsion Systems)						
Internal Combustion Engine	75	170	2,000	50–100	Demo	Fuel fire
Diesel Engine	125	75	1,000	100–200	Demo	Fuel fire
Brayton-Lithium Sulfur Hexafluoride ($LiSF_6$)	400	700	1	15	Demo	Fuel fire
Stirling	200	250	2,000	50–100	Proven	Fuel fire

* Battery parameters are based upon single cells; nonbattery performance parameters are system level.

c. Nonrechargeable Batteries

Available primary batteries, which cannot be recycled and which are discarded upon depletion, are also shown in Table 13.2-6. Applications are electric torpedoes and military UUVs, like the long-term mine reconnaissance system (LMRS) with its $LiSoCl_2$ primary battery, for which high energy density outweighs cost of a one-cycle energy source.

See Section 7 for more on battery systems.

Table 13.2-7. Performance of State-of-the-Art and Advanced Battery Systems

Battery System	W-h/kg		W/kg		W-h/liter		$/k W-h		Problems
	Now (to 2000)	Future (2020)	Now (to 2000)	Future (2020)	Now (to 2000)	Future (2020)	Now (to 2000)	Future (2020)	
State-of-art lead-acid	35	40	110	150	80	100	150	100	Low energy density, fairly high self-discharge
Bipolar lead acid	38	50	—	79	—	85	—	100	Costs more than conventional lead-acid, low specific power
Na/S Ni/Cd Zn/Air	90 35 90	120 40–50 140	110 50–60 100	140 80–90 150	140 80 —	180 90–100 —	1,000 250–300 —	100 200 35–45	Operates at 350 °C. Sensitivity to overcharge. System weight dominated by electrolyte weight. Low energy efficiency.
Al-Li/FeS	80	150–200	95	180–220	—	—	High	100	Operates at 400 °C

Source: Board on Army Science and Technology, 1993, "Electric Power Technology for Battle Zones," STAR 21: *Strategic Technologies for the Army of the Twenty-First Century*, National Academy Press, Washington, DC, Table 43-5, p. 571 (from Naval Studies Board, Vol. 2, 1997).

Table 13.2-8. Energy Densities of Various Battery Systems in Practical Values During a 5-hour Discharge Period (Source: Naval Forces, 1995)

Battery	Energy Density	
	Gravimetric (W-hours per kilogram)	Volumetric (W-hours per liter)
Lead Acid	35	100
Nickel Cadmium	30–40	80–130
Nickel Metal Hydroxide	60	175
Lithium Ion	100	200

B. DRIVE SYSTEMS

On any naval vessel, the transmission and drive system:

- Transmits power from the power source to the propulsor;
- Adjusts the speed of the rotating shaft from the power source speed to the desired rotative speed for the propulsor;
- Provides coupling of one or more power sources to each propulsor; and
- Cross connects the power sources so that a minimum number of power sources need be operated to power the vessel's propulsor shafts.

Mechanical or electric drive systems are used in almost all if not all existing naval vessels (Simmons et al., 1991).

1. Mechanical Drive

Diesel engines operate at very high speeds, and large gas turbines spin up to 3,600 rpm. Propellers, on the other hand, are generally most efficient at 100 to 200 rpm. To allow the engine (prime mover) and the propeller to operate at their most efficient speeds, mechanical reduction gears are used to lower the high output speed of the prime mover to the lower speed required by the propeller. A second function of the reduction gear is to combine the output of two or more turbine shafts to power a common propulsion shaft. The main disadvantage of mechanical gears is their noise. Optimizing tooth and casing designs to reduce noise is difficult over the range of shaft speeds that are used (Simmons et al., 1991). Another disadvantage in gas-turbine-powered craft is the degraded power density of the propulsion system because the weight of reduction gearing may exceed the weight of the power generator (Brown and Lee, 1993).

2. *Electric Drive*

An alternative to mechanical gearing for matching most efficient engine speed to most efficient propeller speed is electrical transmission with a propulsion motor running at a fraction of the speed of a propulsion generator. During World War II, the United States produced many turbo-electric vessels, in part because of a shortage in gear-cutting capacity (Wood, 1995). With the end of the war, the industrial gear-cutting capability improved, and electric drive systems were not competitive with mechanical geared systems. Electric machinery was too heavy and inefficient (Krolick, 2000; Simmons et al., 1991). That state of affairs has changed over recent years. “The advent of fast, high-voltage, high-power semiconductor switching devices is revolutionizing the commercial marine industry—cruise ships, ferries, and shuttle tankers” (McCoy, 1998). The move to electric drive systems for commercial and military vessels is driven by the development of power electronics; improved electric motors and generators; development of high power-density, aircraft-derivative gas turbine engines; and growth in electric power loads in nonpropulsion applications (McCoy, 1998; Krolick, 2000; Simmons et al., 1991; Tucker, 2000).

By utilizing electric drive and integrating ship’s service and combat systems power through the use of rapidly developing power electronics, all installed ship power will be available in flexible electric form. See Figure 13.2-9 for schematics of power system architectures. With an IPS, naval vessels will be able to apportion power to propulsion, ship’s service, and combat systems, as the situation requires. At present, 70 percent to 90 percent is dedicated to propulsion (IPS Review, 2000). The IPS will need fewer prime movers, as illustrated by Figure 13.2-10.

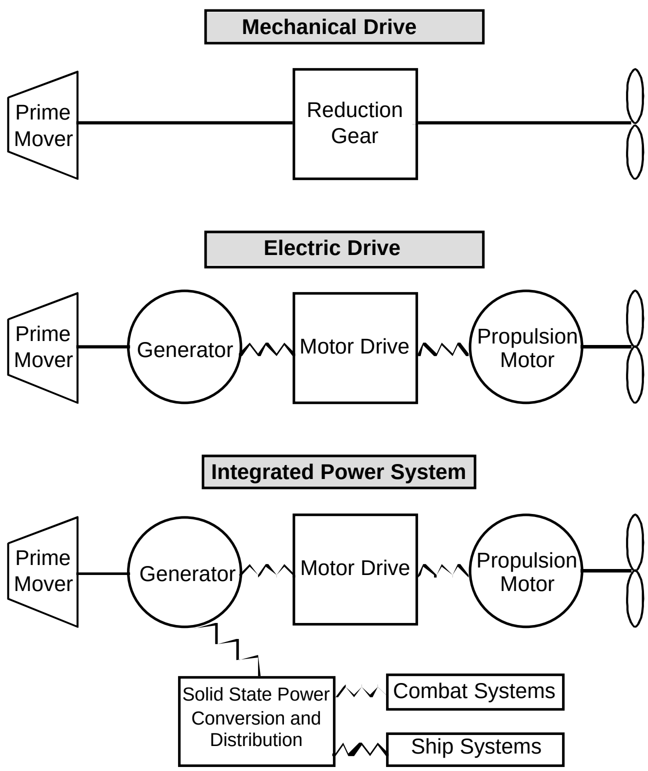

Figure 13.2-9. Comparison of Power System Architectures

In the IPS, existing Navy-qualified engines can be used as prime movers. The electric propulsion power train can be contrasted with the mechanical power train used today on most Navy ships. A recent IPS review (*IPS Technology Review*, 2000) for the Secretary of the Navy indicated that by replacing the gearbox with a generator, motor drive, and propulsion motor:

- The generator can supply all shipboard power demands, eliminating dedicated turbine generators for conventional electrical loads;

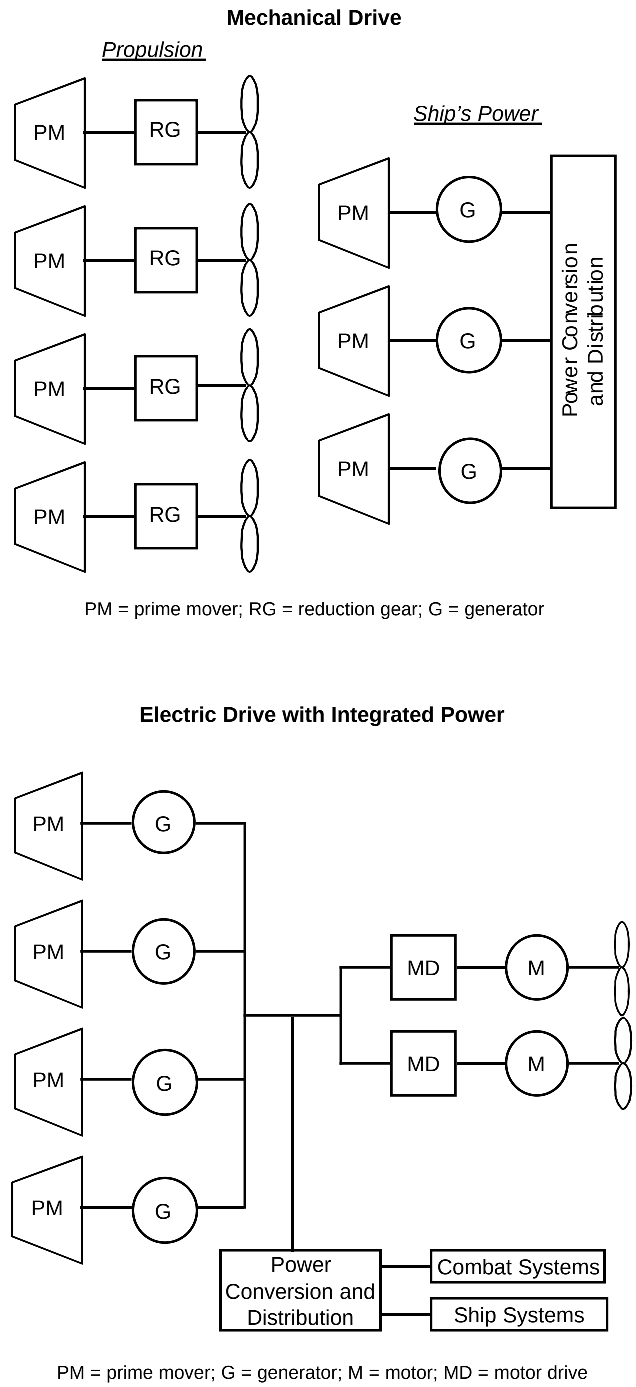

Figure 13.2-10. The Advantage of Integrated Power

- The motor drive controls the speed of the propulsion motor, eliminating controllable pitch propellers on gas turbine ships; and
- The motor provides smooth torque to the propeller, eliminating gear noise.

Some benefits of an IPS can be attained by this architecture independently of the technology utilized. For example, commercial ships utilize relatively low-technology machinery in their IPSs.

With fewer prime movers, the IPS saves fuel, reduces maintenance requirements, and improves noise signature. A recent *Proceedings of the Naval Institute* summarized the advantages of an integrated electric warship:

- *Fuel consumption*—Greater than 15–19 percent savings over existing gas-turbine combatants when operating a minimum of two generator sets.
- *Engine maintenance*—Reduced by nearly 50 percent over existing ships.
- *Propulsion shaft*—Either eliminated [by use of pods] or shortened by more than 50 percent. Short shafts reduce propulsion drive-train construction costs and vulnerability to weapon damage.
- *Propulsors*—Reversible electric motors allow use of fixed pitch, ducted, pre- or post-swirl, or other advanced types for better efficiency and reduced acoustic signature.
- *Flexibility/upgradability*—Allows for combat systems upgrades using significantly more electric power. Because the speed-power curve for a ship is a cubic (speed proportional to power cubed), doubling ship service load will cause negligible loss in top speed for a typical destroyer.
- *Increased automation*—Requires automated power-management systems because electrical transients occur too rapidly for the "man-in-the-loop" control typically used on today's ships. Automated start-up, reconfiguration, and power management are facilitated by modern solid-state controlled power systems.
- *Signatures*—Fewer prime movers operating and reduced fuel consumption improve infrared signature. Advanced propulsors and quiet electric machinery improve acoustic signature beyond what is capable with today's mechanical-drive ships.
- *Naval architecture*—Gives the ship designer flexibility in locating large prime movers and other support systems not possible with traditional systems. This allows the high-value space on the ship to be used by the mission payload of the ship.
- *Payload capacity*—Reduced machinery compliment and increased fuel efficiency allow the same size ship to carry more payload, go farther, or stay on station longer (McCoy, 2000, p. 55).

Electric drive propulsion offers advantages for nuclear attack submarines (SSNs). Efforts to minimize acoustic radiation from machinery may be at or near the limits of achievable levels. Electric motors would enable current mechanical limitations to be circumvented by better control of radiated noise. An integrated electric propulsion system would allow flexible assignment of energy. The large quantity now fenced off for propulsion, and thus unavailable elsewhere, could be used at low speeds for launching weapons, for example. A "direct conversion" reactor in all all-electric SSN, would eliminate requirements for turbines and other power plant machinery (Defense Science Board Task Force, 1998).

The major components of electric drive systems are propulsion motors, generators, motor drive, and power conversion.

a. Propulsion Motors

The Navy's IPS program uses the following logic chain to seek more power-dense propulsion motors:

- Propulsion power is proportional to ship speed, so a faster ship requires a higher power motor;
- Propeller noise can be reduced, for a propeller of the same ship speed rating, if the propeller transfers the required power at a lower rpm (lower shaft speed);
- Motor torque is power divided by shaft speed, so a quieted, low-speed propeller requires a higher torque motor;
- For any type motor, motor torque determines the size of the motor; therefore reducing propeller noise requires a larger motor; and
- Motor size can be reduced by using a higher torque motor in the same volume (*IPS Technology Review*, 2000).

The IPS program uses several measures of motor performance for discriminating among motor types for naval propulsion applications (*IPS Technology Review*, 2000):

- *Acoustic performance*—The noise produced by the motor is reduced by larger air gaps and an increased number of poles.
- *Power density*—Naval applications limit the volume available to produce a given amount of power.
- *Electrical efficiency*—Induction and wound field motor electrical efficiency is improved by smaller air gaps and fewer poles.
- *Consequences of electrical faults*—The ability to manage an electrical fault and continue operation of the motor is an important consideration.
- *Development cost*—The amount of Navy and commercial experience with design and manufacture of propulsion-size motors provides an indication of probable development cost.
- *Unit cost*—The cost of motor materials, design, and manufacture.
- *Reliability*—Naval propulsion motors must have long-term reliability under adverse conditions, including shock.

In considering various propulsion motors, the IPS program assessed wound field synchronous motors, which are widely used for high-power applications, as requiring a very large motor volume for a given power level. And the IPS program induction motors, which are simple and rugged, are less efficient than other types of motors, and trade-offs between size and acoustic performance limit their use for surface ship propulsion and prohibit their use in submarine propulsion (*IPS Technical Review,* 2000).

Because of their acoustic and power density characteristics, permanent magnet (PM) motors have been developed for many pump applications. IPS program rationale for PM motors is that "compact permanent magnets also permit a larger number of magnetic poles. For a given power level, a larger number of poles allows the electrical load carried by each pole of the stator's rotating magnetic field to be reduced. This results in a smaller stator thickness, which reduces the overall size of the motor. This reduction in stator thickness is key in enabling a simple, but very effective cooling of the stator windings by water cooling of the stator." The PM motors are high-efficiency, small-volume machines that achieve greater torque density than either wound field synchronous or induction motors (*IPS Technology Review,* 2000). Assessments of PM machines in Europe as reported in a 1995 *Naval Forces* journal had the following conclusions:

> PM machines with very high power and torque densities have been developed and hold great promise for submarine applications. The characteristics of these machines can be tailored to provide the highest possible efficiencies over a very wide speed range, while meeting all the critical shock and noise requirements for shipboard installations. A high degree of modularity and commonality in the power electronics and controllers can further reduce acquisition and logistic support costs. In space and weight limited installations, the compactness of PM machines can have a very significant impact on overall system costs.
>
> New uses can also be envisioned, based on the unique characteristics of PM machines. They are completely reversible and can function equally as motors, generators, or brakes. Their great flexibility in configuration allows them to be fully integrated into other equipment, such as sealless pumps.
>
> PM machines are finding ever more applications in the high-power commercial market and industrial markets and are achieving long lives with very high degrees of reliability. In short, PM technology has now reached the level of maturity that allows it to be reliably applied to many aspects of advanced submarine electrical systems (Gellatly et al., p. 73).

And an assessment by a NATO study on an all-electric warship described in a more recent 1999 *Naval Forces* journal concluded that:

> Permanent magnet technology for propulsion motors can be considered the way ahead with radial [flux] for short and axial or transverse flux for long-term offering up to 50 percent saving in volume and weight over conventional machine (Weigel, 1999, p. 49).

Superconducting homopolar motors, which are under development, are another type of propulsion motor that will provide increased power density. These motors use cryogenic cooling of superconducting material to create high currents within electromagnets, which produce very high strength magnets. The use of a static field and DC power avoids potential noise problems, thereby making these motors very quiet (*IPS Technology Review*, 2000). Homopolar motors, which are the only DC electrical motors, produce very smooth torque because they have no magnetic field pulsations or alternating currents. Their inherent low noise generation, high power density, and efficiency make them well suited to naval propulsion systems (Walters et al., 1998).

b. Generators

Most shipboard generators in the Navy are derived from commercial units. An exception is submarine turbine generators, which have higher performance requirements. The drivers in generator design are prime mover efficiency, generator rotor diameter, size, and weight (*IPS Technology Review,* 2000). The favorable assessments of PM machinery reported in *Naval Forces* journals above apply to generators as well as propulsion motors. A special 1999 issue of the *Naval Forces* journal reported that the German Class 212 submarine will be equipped with a PM propulsion motor and gave the following outlook for PM generators (Hollung, 1999):

> The high flexibility and compactness of PM machines qualify them for use in future drive concepts. [A 1,700-kW PM generator of a test ship was 40 percent smaller than a 1,000-kW synchronous submarine generator.] The gain in space can be put to good use during the conversion of existing submarines, for example, to reduce the size of an AIP section during a mid-life conversion.
>
> PM generators are more expensive than conventional generators, but this is easily offset by the reduced length of the hull, and increased use of this technology will lead to a significant decrease in price.
>
> Compact PM drives could also replace hydraulic drives because they are more efficient and easier to control. Because of its compactness and high level of redundancy, PM technology will be increasingly employed in future submarine designs (p. 43).

c. Motor Drive

Propulsion motor drives are electronic power converters that produce variable voltage to control motor speed. The IPS program judges

> [The] development of acceptable motor drive technology to be more challenging than the development of motor technology. Improvements in these drives result from improved semiconductors in the commercial market. These devices allow motor drives to be more power dense and have less distortion which is important for acoustics and efficiency. Compared to commercial marine drives, Navy applications process more power for a given ship displacement and must have much less distortion for acoustic reasons. Advanced Technology drives can be beneficial to all motor types. Improvements to generators and other system connected components can result from improved drives. [Drivers for designing motor drives are] acoustics, power, voltage, cooling, size, and shock (*IPS Technology Review,* 2000, pp. 31, 32).

Motor drive technology options—line commutated and cycloconverter—used by commercial marine vessels produce high levels of distortion, which produce high levels of acoustic noise. The Navy is developing a 19 MW pulse width modulation (PWM) method of using power electronic switches in the motor drive to create a waveform of the needed frequency. The method uses short pulses of varying widths to approximate the wave shape. Using more pulses (higher switching frequency) gives a better approximation. The Navy is demonstrating a motor drive that, because it does not use a transformer, switches at high voltages and is limited to 2 kHz. Higher switching frequency designs produce better waveforms with low distortion.

The advantages of a PWM converter over a line-commutated inverter or cycloconverter are described at the 1998 International Conference on the Electric Ship (Benatmane, 1998):

> A PWM converter was selected over a load commutated inverter (LCI) or cycloconverter for numerous reasons. Since a PWM converter does not require a synchronous motor to maintain a controlled load commutation, the advantages of an induction motor become available with the PWM drive. The PWM converter provides the ability to control the waveform for a more sinusoidal shape. This reduces harmonics resulting in lower motor noise than is possible with other converters. Other advantages of PWM converters over LCI and cycloconverters are a higher, more constant power factor for better efficiency, constant harmonic frequencies to ease any supply filtering required, and smaller size and weight (p. 4).

d. Power Conversion

As in the case of motor drives, conversion of power for ship's service and combat systems will benefit from advances in power semiconductors. The outlook expressed in the *IPS Technology Review* (2000) is that:

> Size can be reduced as new devices and advanced circuit architectures are applied. Improved power quality can reduce the acoustic noise from electric equipment throughout the ship and, therefore, is an important factor in power conversion development. Large cost benefits can be realized in the development of power conversion through coordinated developments to increase the level of modularity and commonality among various pieces of equipment and components (p. 37).

e. More Power Electronics

Advances in power electronics are expected to include universal (any ship) integrated power modules that integrate microprocessor and high power density semiconductors. These programmable, multifunction devices, power electronic building blocks (PEBBs), will replace separate unique control devices, such as transfer switches, circuit breakers, adjustable speed drives, power supplies, and inverters. The PEBBs sense what they are plugged into and what is plugged into them and then make the electrical conversion with their software programming capability. The incorporation of PEBBs is expected to provide these performance gains in power electronics components:

- Reduce the weight, size, and cost by 10×;
- Increase current density, speed, and reliability by 10×; and
- Increase voltage capability 3×.

This modular component concept is applicable to power requirements of all ships (Ericsen, 1999; Tucker, 2000; Campisi, 2000).

C. PROPULSORS

Propulsors include propellers and waterjets. Propellers are external marine propulsors that work outside a ship's hull. Waterjets are internal marine propulsors, as shown in Figures 13.2-11 and 13.2-12. There are several screw-type propellers, which are distinguished by their abilities to accommodate the effects of cavitation. Cavitation is the formation and collapse of vapor-filled bubbles, or cavities, that cause noise, vibration, and often rapid erosion of the propeller material, especially in fast, high-powered vessels. As long as the rotational and translational speeds of the propeller are not too high, the onset of cavitation, which is underwater noise, can be delayed or limited to an acceptable amount by clever design of blade sections. With the availability of high-speed computers, improved design procedures, and better mathematical models of propeller hydrodynamics, cavitation onset speed is increasing (Friesch and Praefke, 1997; Gangler, 1997; Shelde Shipbuilding, 1998). Within a very few years, cavitation onset speed will improve from 15 knots in the recent past to 25 knots (Tucker, 2000).

Figure 13.2-11. Waterjet

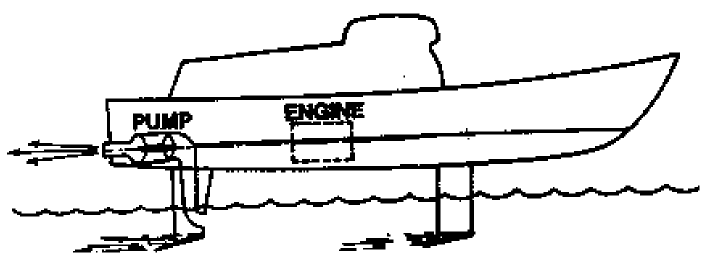

Figure 13.2-12. Waterjet Propulsion on a Hydrofoil Craft (Source: Gillmer, 1970)

The screw propellers can also be distinguished by the number of blade rows they contain. Those with one blade row are designated single component subcavitating propellers. Multiple component propellers include two or more rows of blades and often other components as well; they are designed to provide efficient propulsion when a large amount of thrust is required and when the advance ratio (ratio of a vessel's forward speed to the tip speed of the propeller) is large (e.g., when a high-speed vehicle is outfitted with a small-diameter propeller.

Cavitation tends to degrade the performance of conventional fully wetted (submerged) propellers at speeds above 30 to 35 knots. To obtain higher speeds, propellers designed for partially or fully cavitating flow must be used. Transcavitating propellers were developed for speeds lower than those for full cavitation (i.e., about 30 to 35 knots). Supercavitating and superventilated propellers enable vehicles to be propelled efficiently where full cavitation exists. These two types of propellers are described by the *McGraw Hill Encyclopedia of Science and Technology* (1997):

> Supercavitating and superventilated propellers are designed to have fully developed blade cavities which spring from the leading edge of the blade, cover the entire back of the blade, and collapse well downstream of the blade trailing edge. The blade of such propellers has unique sections which usually are wedge-shaped with a sharp leading edge, blunt trailing edge, and concave face. Supercavitating and superventilating propellers are distinguished by the nature of the gases in the cavity. Supercavitating propellers have cavities filled with water vapor and small amounts of gases dissolved in the fluid media. Superventilated propellers have cavities filled primarily with air or gases other than water vapor; they may be fully submerged propellers with a gas supply system through the propeller shaft and propeller blades into the cavity, or partially submerged propellers which draw air from the water surface as the blade enters the water.
>
> Both of these propeller types are intended for use in high-speed craft (speed greater than 45 knots or 83 km/h) such as hydrofoil boats, surface-effect ships, and the higher speed planing craft with high propeller-shaft rotational speeds (p. 473).

Advantages, speeds, and applications of various types of propellers are shown in Table 13.2-8.

A very frequent issue in propulsion plant design is the choice of controllable-pitch or fixed-pitch propellers. The *McGraw-Hill Encyclopedia of Science and Technology* (1997) discusses some considerations in making the choice:

> For ships which normally operate at widely varying speeds and propeller loadings (towboats, rescue vessels, trawlers, and ferryboats), the application of controllable-pitch (rotatable-blade) propellers permits the use of full engine power at rated rpm under all operational conditions, ensuring maximum thrust production, utmost flexibility, and maneuverability. Since these propellers are also reversible, they permit the use of nonreversible machinery (gas turbines). The hydraulic or electric servomotor for adjusting the pitch of the blades requires a hollow tailshaft for its operation. The propeller pitch can be directly controlled from the ship's bridge. In each case the operational advantages of the controllable-pitch screw must be weighed against the disadvantages of more complex construction and higher manufacturing cost (p. 473).

The waterjet is a different type of propulsor. As an alternative for countering propeller cavitation problems for high-speed craft and special-purpose craft, the waterjet, which is driven by a gas turbine, provides a jet-reactive thrust of high-velocity water expelled through a nozzle. With a speed range above 45 knots, waterjets, whose principal advantage is improvement of vehicle maneuverability over the whole speed range, are typically applied to patrol boats, surface effect ships, hydrofoils, and motor yachts. Kamewa waterjets have been installed on more than 500 craft since the early 1980's. Experience of these units is reported by Kamewa to demonstrate other operational benefits (Croner, 1997):

- Good fuel economy. Above 20–25 knots usually competitive with propeller propulsion for the actual types of craft;
- Reduced internal noise and vibration levels compared to propeller propulsion. Noise reduction usually 7–10 dBA;
- Reduced hydroacoustic noise, usually about 10 dBA;
- Power absorption at constant rpm is insensitive to the ship's speed;

Table 13.2-8. Screw Propulsors
(Source: Simmons et al., 1991, and Kennell, 1995)

Type	Principal Advantage	Speed Range (knots)	Typical Applications
Single Component Subcavitating Propellers			
Fixed Pitch	Relatively high efficiency at lowest initial cost	<30	Smallest pleasure craft to crude carriers over 400,000 tons
Controllable Reversible Pitch	Enables astern movement by turbine-powered vessels without need for reversing gear or separate astern turbines	<30	FFG-7 CG-47 DD-963 DDG-51 Workboats Fast ferries
Ring Propeller	Enables better performance at high thrust loading	<15	Tugs
Accelerating (Kort) Nozzle	Enables better performance at high thrust loading	<20	Tugs Ice breakers
Decelerating Nozzle (Pumpjet)	Enables higher cavitation-free speed	<20	Torpedoes
Steerable Nozzle	Increases maneuverability at low speeds	<20	Tugs Fireboats
Mitsui Integrated Duct	Increases propulsion efficiency	<18	Crude oil carriers over 200,000 tons
Padded Propulsor	Reduces volume and weight of propulsion system inside ship	<32	Open stern vessels like destroyers
Multiple Component Subcavitating Propellers			
Tandem	Divides load over two propellers	<35	Tugs Passenger Vessels
Contrarotating	Provides large increase in propulsive efficiency	>40 (torpedoes) >35 (ships)	Torpedoes High Speed Pleasure Boats Submarines
Pre-swirl Vanes	Improves efficiency Reduces signature	>40 (torpedoes) >35 (ships)	Torpedoes Coast Guard Utility Boat Padded Pusher Propeller Commercial Ships
Ducted Propeller with Pre- and/or Post-swirl Vanes	Improves efficiency Reduces signature	>50 (torpedoes) <35 (ships)	Submersibles Torpedoes (MK 48, MK 50) Destroyers Tankers Cargo Ships
Vane (Grim) Wheel	Improves efficiency	<30	Motor Launch Cruise Ship
High-Speed Propellers			
Transcavitating	Increased efficiency and reduced vibration and erosion at design speed	<50	
Fully Submerged Supercavitating	Enables high-speed operation with good efficiency	40–70	High-speed planing craft Hydrofoils
Partially Submerged Supercavitating*	Increased efficiency by reducing propulsor appendage drag	50–90	SESs Hydroplanes Hydrofoils High-speed planing craft
Superventilated	Enables fully cavitated operation at lower speeds	35–40	

* Includes the semisubmerged (50 percent of the blade is submerged) supercavitating propeller.

- Diesel engines are not over torqued or over speeded;
- Reduced engine wear;
- Cruising units can be used at full power during cruising as well as at top speed together with booster unit;
- Shallow draught and protected installation; and
- Well proven, reliable design.

Another propulsor that was first used on torpedoes and adopted for submarines—UK's Trafalgar-class SSNs and the U.S.'s Seawolf SSN—is the pumpjet, which is also discussed in Section 13.4. The pumpjet is essentially an axial turbine pump consisting of a duct or shroud surrounding a fixed stator with radial slots that twist the direction of water flow and a rotor with more blades than a conventional propeller. Figure 13.2-13 shows a pumpjet on a Swedish submarine model. This cylinder arrangement increases propulsive efficiency and lowers noise by reducing tip vortices. The pumpjet on the Navy's Seawolf is both quieter and more efficient than an open propeller (Zimmerman, 1993; Scherr, 1996).

Figure 13.2-13. Pumpjet Propulsor Mounted on a Model of the Västergötland Class Submarine (Source: SSPA Sweden AB)

D. ELECTROMAGNETIC PROPULSION

The magnetohydrodynamic (MHD) system was described 30 years ago as an interesting propulsion system in the realm of the esoteric and improbable. But it should not be discarded because, like waterjets, which had recently been in that category, development may prove MHD to be applicable to submersible vehicles (Gillmer, 1970). In the simplest form of MHD systems, DC voltage is impressed across electrodes that span or surround a thruster unit through which seawater is flowing. A magnetic field is applied perpendicularly to the electric current. The resulting force field accelerates water passing through the thruster. The reaction force moves the vehicle through the water as shown by the schematic in Figure 13.2-14. The thruster imparts momentum to the water in a direction opposite that of the vessel's motion. The thrust of the vessel is the reaction that is equal and opposite the force acting on the water. The DC system has no moving parts (no blades or vanes) and should provide uniform thrust and operate very quietly.

The disadvantages of propelling vessels by directly applying electromagnetic current were identified 30 years ago as:

> [Poor] efficiency of energy conversion of permanent magnets. Superconducting magnets of more contemporary design have solved this difficulty in more recent designs. There still remains the large size of the required propulsors needed for surface ships with their accompanying drag, the great weight of the coils necessitated in the induction system, the stresses on the structure resulting from the forces produced, the heat transfer problems, and a formidable list of associated mechanical and design problems (Gillmer, 1970, p. 191).

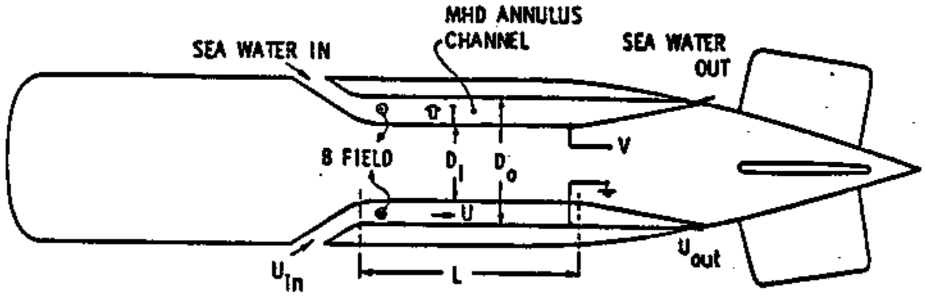

Figure 13.2-14. Submersible Body with Integrated MHD Propulsion.
Source: Lin, T.F., Gilbert, J.B., and Kossowsky, R., *Sea-Water Magneto-hydrodynamic Propulsion for Next-Generation Undersea Vehicles*, Penn State ARL Annual Report, 1 February 1989 to 31 January 1990 (Simmons et al., 1991)

In an examination 20 years later of MHD for naval propulsion systems, Simmons et al. (1991) report the principal difficulty limiting MHD propulsion is the relatively low conductivity of seawater. To obtain sufficient thrust to move a ship, it is necessary to interact a very substantial current with a high magnetic field. Even with extremely high levels of magnetic field, the numbers obtained for efficiency are low. The investigation team cited an example of a propulsor at a speed of 15 knots achieving a propulsive efficiency of 30.7 percent.

> Because MHD thrusters have losses that depend on thrust and since power output is the product of thrust and speed, MHD propulsors become more efficient, for a give thrust level, as speed increases. That might indicate that a ship running at 30 kn might have an acceptable efficiency. The trouble is that this thruster is assumed to have a flux density of 10 tesla (T), a cross-sectional area of 3.85 m^2, and a length of 20 m. (In the example, flux densities of more than 5–10 T are highly speculative.) In magnets of that size, fields of that intensity are unheard of (p. 260).

Further, the investigators know of no magnet systems that could produce such a high flux density field—about 23,000 psi equivalent magnetic pressure—for a 30-knot MHD system with about 30-percent electric efficiency. They say that achieving the high flux densities required will in turn require much stronger, lighter structures than are currently envisioned. They report that:

> Interest in MHD has persisted, in spite of its low predicted efficiency, because investigators have assumed that MHD propulsors are inherently quieter than screw propellers since they do not have any moving parts. While MHD may turn out to be very quiet, it is not known…that this has ever been demonstrated in practice. The high densities and magnetic field strengths required could, in fact, create noise through excitation of the hull structure or by bubble formation at the electrodes. Other potential noise sources that should be considered are those associated with flow noise through the duct, especially at the inlet and exit. Even if the MHD can be shown to be very quiet, applying this technology to naval vehicles will require verification that the high magnetic fields do not create other easily detectable signatures (p. 261).

In summary, the MHD could potentially radiate little noise since it has no mechanical parts that make direct contact with the water. But the MHD has a very low propulsive efficiency; requires large, costly superconducting magnets with elaborate cooling; and requires lots of power (Simmons et al., 1991).

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LIST OF TECHNOLOGY DATASHEETS
13.2. PROPULSION

Technology Name **Page**

DATA SHEET 13.2. INTERCOOLED RECUPERATED GAS TURBINE

Developing Critical Technology Parameter(s)	Fuel efficiency relative to a simple-cycle gas turbine of the same power level.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial vessels with gas turbine prime movers will be interested in the ICRGT.
Affordability	The ICRGT is expected to use 30-percent less fuel than a comparable simple-cycle gas turbine.

BACKGROUND

On the basis of efficiency, complexity, and cost of ownership, the ICRGT is superior to diesels or simple gas turbines for a blue-water navy.

DATA SHEET 13.2. HEAT ENGINE AIR-INDEPENDENT PROPULSION

Developing Critical Technology Parameter(s)	Submerged endurance of diesel-electric submarines relative to battery-only endurance. Heat engine (or combustion engine) AIP includes three types that are in advanced development or in operation: CCD/Stirling and closed Rankine cycle.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	No commercial applications are expected.
Affordability	Not an issue.

DATA SHEET 13.2. FUEL CELL

Developing Critical Technology Parameter(s)	There are two parameters for marine fuel cells, which are an electrochemical form of AIP: (1) submerged endurance of diesel-electric submarines operating on fuel cells relative to battery-only endurance and (2) acoustic signature of diesel-electric submarines operating on fuel cells relative to battery-only signature.
Critical Materials	Hydrogen-rich material—natural gas, methanol, kerosene, diesel fuel—from which hydrogen can be produced by reforming the hydrocarbon gases and liquids. The absence of sulfur and other impurities, which pollute petroleum distillates and which must be removed prior to the reforming process, is vital.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Given diesel reforming, fuel cells would be attractive for commercial vessels that operate on diesel fuel.
Affordability	Not economically attractive without diesel reforming. Cost per kilowatt produced by fuel cell is expected in a decade be the same as the cost of a kilowatt produced by a diesel engine.

BACKGROUND

Fuel cells will provide silent, efficient auxiliary propulsion systems. They are a high reliability, long-life, low-maintenance form of AIP. They will operate as quietly as batteries.

DATA SHEET 13.2. DIESEL REFORMING

Developing Critical Technology Parameter(s)	Producing hydrogen from the fuel that powers most naval and marine vessels.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Two sets of equipment are required: (1) that used in the reforming process to produce hydrogen and (2) equipment for the purification process that must filter out sulfur and other impurities in the diesel fuel before reforming.
Unique Software	None identified.
Major Commercial Applications	Applicable to any commercial vessels that operate on diesel fuel.
Affordability	The cost to purify and reform diesel fuel as well as the overall efficiency of the fuel-cell energy-generation system will not be known until a later stage of development.

BACKGROUND

This technology would enable naval and marine vessels to use fuel cells without having to carry another fuel.

DATA SHEET 13.2. ELECTRIC DRIVE

Developing Critical Technology Parameter(s)	Today’s surface ships are constructed with mechanical or geared-drive propulsion and segregated electric-power systems. Electric drive in an IPS enables total power available on many types of ships to be flexibly apportioned as needed for propulsion, ships service functions, and combat systems.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Electric drive has already been adopted for cruise ships and other commercial vessels.
Affordability	An IPS with electric drive will reduce the number of prime movers, fuel consumption, engine maintenance, and manning.

SECTION 13.3—SIGNATURE CONTROL AND SURVIVABILITY

Highlights

- Advances in and proliferation of sensor technologies will increasingly drive future naval warfare.
- Improvements in target acquisition and missiles, mines, and torpedoes make avoiding detection more important in ship design than speed and maneuverability.
- Thus, the application of stealth technologies is imperative for maintaining an effective naval force.
- Automating fire protection and fluid system management will enhance ship survivability and reduce manning.

OVERVIEW

Reducing susceptibility to attack through signature control is an imperative for survivability of naval vessels on or under the sea. Survivability depends on low susceptibility to damage achieved by reducing the detection range of threat sensors, making classification, tracking, and targeting more difficult, and by improving the effectiveness of countermeasures (CMs). Given a hit, survivability is enhanced by integrated sensing and by actions to quickly and automatically detect, characterize, and control fire, flooding, and/or structured damage (Naval Studies Board, Vol. 6, 1997).

The technologies to enhance signature reduction and increase survivability of future naval platforms are discussed below. See Section 18 for more on marine signature control as well as signature control in general. Signatures of naval propulsion subsystems—prime movers, motors and generators, motor drive, and propulsors—are discussed in Section 13.2. Signatures and signature control of submarines and other undersea vehicles are discussed in Section 13.4.

A. SIGNATURE REDUCTION

1. Acoustic

Surface ships and submarines emit high levels of underwater noise that can be detected and tracked by passive sonars. And the noise can also interfere with a vessel’s own sonar, thereby reducing its effectiveness against submarines. Because the vessel’s sonar is nearby, the dominant mechanisms that produce self-noise are not quite the same as those that are most important in producing radiation that hostile submarines use for long-range detection. Both self-noise and radiated noise are generated by (1) machinery vibration, which dominates at low speed; (2) flow over the vessel’s hull, which becomes relatively important at speeds above about 10 knots; and (3) propeller cavitation when cavitation onset speed is reached. Machinery typically radiates high noise levels at frequencies corresponding to resonances in machinery vibration. Those spike-like radiations are unlike propeller cavitation noise, the amplitude of which changes little with frequency (Gates, 1987; Enderlein, 1997).

Reduction of machinery noise is especially important in undersea vehicles and antisubmarine warfare (ASW) ships, which search for submarines at low speed to avoid noise from flow and cavitation. Dynamic balancing of moving parts is used in rotating machinery to reduce noise from shafts and connections to other machinery. Some noise will be produced, even with good design and maintenance, and thus, methods of isolating the noise are used on ships and submarines. Equipment is mounted in acoustically insulated boxes that, in turn, are carried on flexible mounts to isolate them from the hull. Large machinery items are sometimes flexibly mounted on “rafts” that are themselves flexibly mounted to isolate the entire machinery installation from the hull. For submarine silencing, further sound isolation is attained by isolating the first raft and others on a second, larger raft. Double-isolation rafting is the reason for the large displacement of modern submarines (Zimmerman, 1993).

Noise-isolation techniques are also used to isolate water inlets and outlets and other items from the hull or flexible mountings so that pipe vibration will not be transmitted to the hull and thence to the surrounding water as noise.

The radiation of machinery-induced noise is also reduced by hull coatings in the form of sound-absorbing anechoic material that transforms incident sound energy into heat. Anechoic panels or tiles are also used on submarine hulls to absorb energy from active sonar and thereby reduce the submarine's echoing area to such transmissions.

Noise can be controlled by active noise-reduction or -cancellation systems or by magnetic bearings specially designed for power transmission systems. These active means incorporate electronic systems that can reduce equipment vibration by generating antinoise or antivibration signals directly to the source.

Hydrodynamic flow noise can be reduced by introducing air bubbles into the flow close to the hull surface (the Masker system); the bubbles damp the flow noise and further isolate the path of machinery noise into the water (Gates, 1987).

Good design of the propeller and nearby hull structure can reduce propeller noise. Ships with low acoustic signatures usually have relatively large-diameter, low-rpm propellers to delay the onset of cavitation. Similarly to the Masker system, the Prairie system introduces high-pressure air through each rotating propeller blade and in some cases from shaft struts to delay cavitation onset. Waterjet propulsors offer lower acoustic signatures than comparable propellers (Brower, 1998).

Mine fuses sense acoustic and magnetic signatures of ships and submarines to detect, classify, and initiate their attack mechanisms. Future mine fuses will be more sensitive and better able to reject noise. Signatures of current and future platforms will have to be reduced commensurately by the use of sound—and vibration—absorbing materials, isolation techniques, and active vibration and acoustic signature control (Naval Studies Board, 1997c).

2. Infrared

Control of thermal signatures has become critical with the proliferation of long-range forward-looking infrared (FLIR) sensors and IR-guided missiles. Controlling IR signatures involves reducing the emissivity of a ship's exhaust gas outlet and plume, as well as its exposed surfaces, which might be outside insufficiently insulated machinery rooms. Hot spots are easier to detect than warm targets (for example, a ship's hull), so hot parts are cooled or screened from direct view of IR-homing missiles. Effective cooling and screening techniques require missile designers to incorporate IR detectors responsive to lower temperatures; they would design imaging seekers that can select large spatial targets and reject point-source decoys. Low-reflectivity paint; low-emissivity, foil-covered windows; and shaping the hull and superstructure to reduce sunlight reflection are also options.

3. Radar

Reducing radar detectability involves three methods to minimize the amount of electromagnetic energy reflected back in the direction of the radar: (1) use structural material that is an absorber or is a poor reflector (dielectric and plastics are better than metals); (2) cover the target object with radar absorbent material (RAM); and (3) shape the target so it scatters the incident energy rather than reflecting it back in the source direction (which a specular reflector does). Absorbent coatings, which can absorb radar signals over a narrow or wide bandwidth, can be applied, in conjunction with shaping, to a new design or to an existing vessel.

Ship images seen by search and fire-control radars at shallow grazing angles can be reduced by above-waterline shaping (hull flare and topside "tumble-home"), the use of RAM, and control of topside reflectors. However, these signature reductions may be ineffective against future satellite-based radars (Brower, 1998).

In a ship's design phase, lower radar cross section (RCS) characteristics can be attained by avoiding round surfaces, right-angle corners, and right-angle intersections of topside longitudinal and transverse bulkheads. Attention should be given to other reflectors: weapons, mooring bollards, anchoring gear, lifelines, topside lockers, ladders, servicing platforms, portholes, pilothouse windows, navigation lights, rails, stanchions, yardarms, and other accessories (Geile, 1997; Brower, 1998). Multifunction planar arrays would be preferred over high-signature conventional antennas. RAM composite panels or modular external sheathing should be considered.

Synthetic aperture and imaging radars can detect characteristic "V"-shaped bow waves generated by ships. This capability will create a long-term detection susceptibility unless the bow wave signature is reduced.

4. *Magnetic*

Vessels can be treated to reduce magnetic signatures by either or a combination of two countermeasure techniques: deperming and degaussing. In deperming, the ship is put inside a coil arrangement, or the coil arrangement is placed around the ship; a powerful electric current is then passed through the coils to create a magnetic field that opposes and thus cancels the ship's own magnetic signature. In contrast, degaussing coils are incorporated in the ship during construction to provide magnetic field corrections; special computer-controlled generators continually feed electric current to the coils, which create an opposing magnetic field that is continually matched to the ship's changing magnetic field. Naval vessels are outfitted with active degaussing systems, and they are also regularly depermed. Commercial vessels usually get deperming treatments only.

Many mines are triggered by a platform's magnetic field. MCM vessels, sweepers and hunters, are constructed with wood, glass-reinforced plastic (GRP), or other nonferrous material. The Naval Studies Board addressed mine fuses and magnetic and acoustic signatures:

> Mine fuses rely on sensing the magnetic and acoustic signatures of ships and submarines for detection, classification, and initiation of their attack mechanism. Expected technology advances in mine fuses will yield improved sensitivity and noise rejection. Unless a commensurate effort is made to reduce the signatures of current and future platforms, their vulnerability to mines will increase in the future. Signature reduction measures that utilize both passive and active signature reduction techniques can be developed and implemented. Enabling technologies include…closed-loop adaptive magnetic degaussing systems and cathodic current reduction (Naval Studies Board, Vol. 7, 1997, p. 52).

Bottom mines—new types and those unused in past conflicts but easily made more potent by incorporating advanced magnetic sensing—are expected to be a threat to ships operating in littoral areas. Intelligent, adaptive closed-loop magnetic degaussing will be needed to significantly reduce the magnetic signature of combatant vessels (Naval Studies Board, Vol. 6, 1997).

5. *Wake*

Most of the following discussion of wake signature is drawn from wake investigation reports by Peltzer (1984), Warner (1977), and Wells (1974). As a ship moves along the sea surface, it generates surface and underwater wakes that can be detected by various sensors systems. Four systems produce imagery from electromagnetic energy coming to passive sensors from exterior sources:

- *Visual* in the wavelength range from 3.8×10^{-5} cm to 7.0×10^{-5} cm;
- *Conventional and infrared photography* in the wavelength range from 3.8×10^{-5} cm to 15.0×10^{-5} cm;
- *Infrared radiometry* in the wavelength range from 7.0×10^{-5} cm to 1.0 m; and
- *Microwave radiometry* in the 0.1-mm to 3-cm wavelength region.

The following systems measure the return energy from active sensors that transmit energy or illumination, and with that returned energy, produce target images:

- *Microwave radar*—in the wavelength range from 1 mm to 80 cm with most systems operating at wavelengths between 0.8 cm and 4.0 cm;
- *Synthetic aperture radar*—in the 1-cm to 10-cm wavelength range; and
- *Acoustic systems*—underwater sound waves scattered by air bubbles in the wake and receive the magnitude of the reflected signal.

Different parts of a ship's sensible wake are visible to the above sensors for varying lengths of time after the ship has passed the location of the sensor. Visibility of different parts of the wake depends on several factors: ship's speed, hull type, propulsion system, and conditions of the sea and weather. The sensible wake can be divided into four regions. In the first region, the foamy, serrated, turbulent, white-water portion of the wake is visible to the above seven sensor systems. After the foam disappears, the wake has a slick appearance as the wake's turbulent core remains visually distinct from the surrounding sea surface. This second region, which is still visible to all seven sensor systems, ends when there is no longer a visual distinction between the sea surface and the wake. In the third wake region, small bubbles remain in thermally mixed water. The wake is no longer visible to the eye, conventional photography, microwave radar, and synthetic aperture radar; the wake is acoustically opaque, but the strength of the return signals is weak and decreases to zero at the end of the third region, when no more bubbles remain. The fourth wake region is only thermally visible because thermally mixed water in the wake and the upper layer of the surrounding sea have not returned to the thermal equilibrium that existed before the ship passed. When the wake surface temperature and the sea surface temperature become equal, the wake is not detectable by any means.

As a submarine moves submerged through the water, wave patterns are generated in the wake, and the jet from the submarine’s screw produces a wake that expands and then collapses. While most of the disturbances remain submerged, small residual effects reach the surface. The effect of primary concern is surface strain, that is, the expansion and contraction of the surface area. The surface strain produces small effects in surface roughness and temperature, which may be detectable from a satellite or aircraft equipment with a sensitive detector. The potential for a synthetic aperture radar to detect disturbances created by passage of a submarine appears most promising. Another possible signature includes the hydrogen that is produced as a waste byproduct and that is discharged into the sea as bubbles by the water-electrolysis method used to produce oxygen for life support. And bioluminescence, which is caused by the propeller/propulsor on micro-organisms, may persist for a period after the submarine has passed (Beattie, 1996).

6. Visual

Stealth measures that are useful against sound, IR, and radar waves are not useful against optical and visual sensors: the visible part of the electromagnetic spectrum is not susceptible to reduction of echoing area techniques. Camouflage, light, smoke screen, and (taking advantage of) clouds are ways to impede detailed target recognition.

A submarine submerged in shallow water might be detectable using visible light; the naked eye could possibly detect a black submarine against a light-colored bottom. Visual detection might also be achieved in shallow water with a blue-green laser system, which depends on the selective ability of blue-green light to penetrate to seawater farther than other wavelengths (Beattie, 1996).

7. Other

Surface ships or submarines produce three related non-acoustic signatures: (1) static electric (SE), (2) corrosion-related magnetic (CRM), and (3) extremely low-frequency electromagnetic (ELFE). All are a consequence of electric currents produced in the water around a vessel’s hull. The SE represents a near-field or mine threat; however, it also contributes to the CRM and ELFE, which might be detachable in the far field (Beattie, 1996).

- The SE signature is a function of materials used to construct a submarine or ship. It is an electric field associated with a direct current generated by the hull-corrosion process. A pair of electrodes can detect this signature as a potential difference measured in seawater. The potential difference is measurable only close to the platform.
- Currents from an in-water CRM signature, which is a magnetic field associated with the static electric signature whose field produces a magnetic flux, are measurable at a greater distance. Detection of the CRM depends on the signature amplitude and the sensitivity of the detection system.
- A cause of the ELFE signature is modulation of electric currents flowing in the propeller shaft. The currents return through the shaft bearing, and as the shaft rotates, the resistance between the shaft and the bearings changes.

Exposed submarine periscopes could be detected by radar. Optronic mast systems, which include visual spectral range imaging and IR imaging, utilize RAM composites to minimize RCS and hydrodynamic shaping to reduce wake signature (Zimmerman, 1993; Duchâteau and Kriese, 1999). Optronic masts reduce detection risk by reducing the length of time the sensor is above water.

8. Lafayette

The Lafayette is one of the first, if not the first, combat ships to be designed from the outset with a stealth imperative for all signature forms. The first of five stealth frigates built by France, it is described, without quantifying levels of signature reduction, by the following ship profile appearing in a 1998 *Naval Forces* journal.

Stealth characteristics are fully integrated into her design. The most obvious stealth feature of the [Lafayette] lies in her highly optimised, low radar cross section shape. Every detail of the hull, superstructure and mast has been designed to reduce the [RCS]: inclined bulwarks, covered foredeck and afterdeck, solid masts with inclined sides, redesigned gun turret and anti-air missile launcher, inclined hull sides, elimination of all right angles as well as all circular shapes, and concealment of ship's boats behind a metal curtain. Most openings are closed at sea by retractable bulwarks. List caused by wind, etc., which would considerably deteriorate the radar cross-section, is counteracted by trimming. Special paint reduces the reflection of electromagnetic waves even further.

The other signatures have also been significantly reduced:

- IR signature with special paints, careful insulation of hot parts and exhaust funnels made of [GRP],
- Magnetic signature by use of a degaussing system,
- Acoustic signature by specially designed rotating machines, use of cradles on flexible mounts and of a "Prairie masker" system (*Naval Forces*, February 1998, p. 50).

B. DAMAGE CONTROL

If signature reduction is not enough to prevent an attack, survivability depends on the ability of naval ships and submarines to cope with the effects of internal and contact explosions, shock waves, and fragments. Given damage by missile, mine, or torpedo, future ship survivability is expected to be enhanced by an integrated intelligent sensing and action system that rapidly and automatically detects, characterizes, and controls fire, flooding, and structural damage (Naval Studies Board, 1997b). Information from MEMS sensors—which determine location of fire or flooding, existence of toxic gas, density of smoke, heat, and structural integrity—will be transmitted via wireless telemetry, along with information on hazardous materials, to suitable displays at damage control central, where decisions to limit damage can be made quickly. The damage control system is expected to have intelligent processors to activate valves and pump controls to trigger reflexive response to damage (Williams, 1999). Automatic fire protection and fluid management will reduce manning levels.

Shipboard machinery space fires present serious challenges to crew members since all elements of a fire are always present—diesel fuel and lube oil, hot metal surfaces as ignition sources, and oxygen through forced ventilation (Maritime Defense, 1997).

1. Firefighting Agents

Shipboard fires generally involve solids (Class A fires) or liquids and liquifiable solids (Class B fires). Halons have been ideal fire extinguishing agents, particularly for fighting fires caused by flammable liquids and explosive gases. They extinguish fires in minimal time, are noncorrosive, and are nontoxic when deployed in at recommended volume densities (Naval Studies Board, 1997a). But halons are related to chlorofluorocarbons (CFCs), ozone-depleting substances, and their production ceased in the United States at the end of 1995. Because of the difficulty in finding a suitable substitute for halon 1301, the Navy will support existing shipboard halon 1301 fire-fighting systems from a strategic reserve until those ships retire (Breslin, 1999). Research and development efforts are examining a range of fire-fighting technologies for new ship construction (Toms et al., 2000). In response to the termination of halon production, the following alternative fire extinguishing systems are being examined: water spray, foam, CO_2, inert gas, and water fog. A report by the manager for deckbuilding technology, pipe systems, and firefighting plants at ROM Schiffban-Dockbautechnik, Hamburg, Germany, identifies the positive and negative features of each system in a special issue of the *Naval Forces* journal:

Water Spray Systems

Positive: not critical with respect to human and environmental aspects like health injuries or environmental pollution.

Negative: free floating water within the vessel causing problems with discharge, stability, etc. In addition big pump capacities (electrical connection value) and relatively large pipe dimensions are needed; water damages.

Foam Systems

Positive: very good fire fighting results even in big fire scenarios and open areas.

Negative: affected areas have to be evacuated, installation of relatively big foam filling pipes and tanks, cleaning-intensive foam damage.

CO_2 System

Positive: very good fire fighting result in closed areas, no damages due to gases.

Negative: critical in view of injuries to health and environmental pollution (green house effect), heavy components (CO_2-bottles) and a relatively high positioned CO_2-room (stability calculation) refilling station.

Inert Gas Systems

Positive: similar to CO_2.

Negative: [similar to] CO_2, where injuries to health seem [not to be critical] if a minimum of oxygen content is ensured.

Waterfog Systems

Positive: [not] critical for human and environment, water is always available; no refilling problems, less weight to be installed; a minimum of free floating water within the decks; automatic and manual release (even several times); no evacuation of affected areas is necessary.

Negative: low visibility.

Based on the above considerations it turns out that water fog technology provides the safest solutions with regard to he vessel’s human and environmental safety (Schmick, 1997, p. 99).

2. *Recovery*

Damage can be expected to cause ship-wide electrical outage and shut-down of combat electronics within seconds. The timeline today to recover combat systems is an interdeterminant number of minutes or hours. Under the Navy’s electrically configurable ship concept in the not too distant future, isolation of damage and immediate reconfiguration of the ship’s electric plant would keep combat systems on line without interruption (Tucker, 2000). Subsection 13.2 has more discussion on this topic.

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TECHNOLOGY DATASHEET
13.3. SIGNATURE CONTROL AND SURVIVABILITY

Technology Name **Page**

DATA SHEET 13.3. DAMAGE CONTROL

Developing Critical Technology Parameter(s)	Automated fire protection and fluid system management.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Automated damage control has already been adopted by the marine industry.
Affordability	Automating damage control will reduce manning, which reduces lifetime operating and support cost of ships. The DD-21 is expected to need 17 persons for Condition III (fighting the ship) damage-control operations versus 110 in the DDG-51. The manning reduction will be about 40 since many of the DDG-51 personnel are needed for Condition I (operating the ship) duties.

BACKGROUND

Automated damage control will reduce casualty response time by 75 percent. It will improve personnel safety through reduced exposure to hazardous environments. And it will reduce manning.

SECTION 13.4—UNDERSEA VEHICLES

Highlights

- The stealth contest will continue as the drive to *operate* stealthy submarines competes with the drive to *detect* them.
- Diesel-electric submarines with fuel cells as AIP, which greatly increases mission endurance, will be as quiet as nuclear-powered submarines.
- But AIP systems do not have the energy density to drive conventional submarines at the high sustained speeds of nuclear submarines.
- Future SSNs will be indispensable multimission platforms because they will have stealth; mobility; endurance; a weapons mix of guided missiles, torpedoes, and mines; off-board vehicles [UUVs and perhaps unmanned aerial vehicles (UAVs)] that extend the SSN's sensor range; and precise targeting information from external sources.
- A new generation of electric ROVs will be lighter, less expensive, more efficient, and require less maintenance than today's electro-hydraulic ROVs; another benefit of electric propulsion for deep-water ROV operations is a much lighter umbilical cable.
- Technology advances in vehicle subsystems and an advantage in economics will enable UUVs to displace ROVs for many underwater tasks just as technology advances and economics have resulted similarly in ROVs displacing DSVs.
- The value of the UUV for the mine countermeasure mission will be realized in the increased area coverage by networked vehicles operating in parallel.

OVERVIEW

This section covers submarines, DSVs, ROVs, and UUVs.

A. SUBMARINES

In the discussion that follows, "submarines" include nuclear-powered ballistic missile submarines (SSBN), nuclear-powered attack submarines (SSN), nuclear-powered guided missile submarines (SSGN), and their conventional (diesel-electric) counterparts (SSB, SSK, and SSG, respectively).

Since the end of the cold war, SSBNs continue to provide strategic deterrence, and Navy planning and preparation have increasingly focused on littoral sea control and power projection across the shore. Mines, antiship missiles, and SSKs will challenge the Navy's ability in the littoral areas (Zimmerman, 1993). Nature provides other difficulties for sea control and power projection operations in the shallow waters of seas covering the continental shelf with depth down to about 200 m. These difficulties were described in a *Naval Forces* journal (Longworth, 1994):

- Sonar conditions are almost invariably poor, and differ radically between any two operational areas—there is no typical shallow water scenario.
- Thermal structures change over hundreds of meters, sometimes radically, and reverberation levels are high.
- Varying tides and currents create highly directional ambient nose levels. The phenomena of the "afternoon effect," whereby contacts fade apparently inexplicably away, is well known.
- Most seabeds are far from benign. Mud absorbs sound. Rocks create false contacts and in a tideway they display Doppler, thus exhibiting many characteristics of a valid target echo.

- [The] above factors are exacerbated if the primary target is a [diesel-electric] submarine because it is smaller, quieter, slower, and more maneuverable than the SSN and may even use the seabed for cover (p. 10).

Shallow depth operations can provide potentially significant nonacoustic signatures: magnetic, bioluminescence, electromagnetic, infrared, and radar/hydrodynamic (masts out of water). In addition, low-search-rate sensors are effective in confined areas (Defense Science Board Task Force, 1998).

The Naval Studies Board of the National Research Council recently studied 21st century technology for the Navy. In its study, the Naval Studies Board identified 10 submarine warfighting objectives that define military capabilities desired by 2035 (Naval Studies Board, 1997):

1. *Sea control*. The exercise of sea control and the certain denial of that control to adversaries are fundamental missions of the submarine. If a submarine is in an operating area, other platforms operate at its sufferance.

2. *Precision strike*. Covert on-station presence, early and for lengthy periods, is necessary in order to identify, observe over time, and destroy when directed potential threat command-and-control nodes and other vital targets with precision submarine-launched missiles.

3. *Covert insertion*. Deployment of ground forces of various numbers, configurations, and capabilities offers the advantage of determining optimum timing by covert and, if necessary, extended on-site observation of the tactical situation.

4. *Coordinated fire support*. Submarines must be able to launch strikes in support of forces both ashore and afloat, utilizing various weapons. In the near future, the OHIO class Trident submarine could be configured to carry and launch between 100 and 200 tactical missiles.

5. *Intelligence collection*. The capability for tactical and national intelligence collection over an extended period is needed to provide forward covert surveillance both prior to and after onset of hostilities.

6. *Theater antisubmarine warfare*. This capability includes protection of sealift, both through constricted littoral areas and in the open ocean, as well as strategic ASW operations conducted against adversarial SSBNs. Strategic ASW encompasses the ability to monitor the activities of potentially unfriendly SSBNs during peacetime, as well as to destroy them when so ordered.

7. *Antisurface warfare*. Attacks against traditional merchant and military targets must include the capability to destroy small, shallow-draft vessels. This capability also supports the submarine’s effectiveness in conducting a blockade, either overt or covert, and in detecting, tracking, and intercepting narcotics or arms control violators.

8. *Strategic deterrence*. The most broadly acknowledged submarine mission area provides the final line of direct defense for the U.S. homeland. As the nation’s most survivable strategic deterrent force, carrying more than half of its strategic nuclear warheads, the Navy’s force of SSBNs requires the continuous infusion of new technology to guarantee its strategic operational security and effectiveness over the decades ahead.

9. *Missile defense*. The future ability of submarine forces to participate as an integral element of the national missile defense (NMD) and theater missile defense (TMD) system, especially as a missile platform forward positioned off a hostile coast, will require further technology development. The potential for boost-phase intercept of enemy missiles and the potential for limited anti-air capability for self-defense and forward-area air-denial operations are both areas of opportunity for further development.

10. *Mine Operations*. Covert mine location, as well as possible disablement by submarines operating in hostile waters, is a prime element in thwarting an enemy’s sea control-denial capability. In addition, the covert and remote placement of mines by submarines can deny an enemy the use of its own littoral waters and severely limit its naval surge potential (p. 86).

The Naval Studies Board identified the following technology areas that are primarily associated with the above objectives: stealth, architecture, sensors and connectivity, payload, and power density.

1. *Stealth*

Stealth is the salient attribute and highest design priority of a submarine. Stealth enables the submarine to operate anywhere, at any time, covertly as a strategic and/or tactical deterrent (Naval Studies Board, 1997). Stealth makes the submarine a good platform for gathering intelligence and for surprise weapon launch. And besides helping to avoid detection, stealth enhances a submarine's ability (by eliminating/reducing self-noise) to detect targets. A major factor in designing power plants for SSKs is minimizing exposure to detection by reducing time a diesel-electric submarine spends snorkeling (*Naval Forces*, 1997).

In the foreseeable future, we expect to see several signature-control efforts for submarines:

- Growing use of anechoic (sound absorbing) and sound-deadening (mass damping) tiles. The anechoic tiles on the hull absorb active sonar transmissions. The sound-deadening tiles inside and outside the hull decouple self-generated noise from the sea; these tiles can be sandwiched to obtain both damping and anechoic effects (Zimmerman, 1993).
- Continued use of noise cancellation, self-noise monitoring, and double- and triple-rafting on SSBNs and SSNs to isolate noise-producing machinery from the hull (Zimmerman, 1993).
- Continued incorporation of optronic masts, which eliminate the optical path of light passing through the periscope. The optronic periscope transmits optical and IR camera images via electronic or fiber-optic cable to a computer, which enhances and records the images, and makes them available in real time to the commander and other crew members. The optronic mast limits hull penetration to wiring only, and hydrodynamic shaping can eliminate flow noise from induced vibration. And the optronic mast aids in removing or reducing the submarine sail, which reduces drag and sonar self-noise (Zimmerman, 1993; Defense Science Board Task Force, 1998).

For more discussion of signature control and stealth, see Section 13.3 and Section 18.

2. *Architecture*

Architecture includes hull structure, shaping, and materials, and other factors such as innovative design and systems integration to achieve better performance (e.g., greater speed and less drag), greater reduction in acoustic and nonacoustic signature, or improved manufacturability. Although stealth is a design priority, the design must enable the submarine to withstand the pressure and shock from underwater explosions at desired operating depths. Circular cross-sections provide the greatest inherent strength, but resistance to compression decreases as diameter/perimeter increases, a characteristic of SSBNs and SSNs in which large volume is needed to accommodate double- and triple-rafting of noise-producing machinery.

Increasing hull thickness to gain strength generates severe weight growth. That circumstance leads to the need to improve steel for the pressure hull. HY (high yield)-80, HY–100, and HY–130 (the numbers indicate pressure strength in 1,000s of pounds per square inch) steel—used in submarines—improvements have resulted either in greater crush depth or in lesser hull diameter. But fabrication and welding problems grow as the stronger steels are used. Titanium, which, unlike steel, is nonmagnetic, is very expensive. Composite materials are superior to steel for their strength and corrosion properties, and they are nonmagnetic. But their use for hulls is problematical due to problems with other properties: flammability, smoke toxicity, shock loading, and usual reactions when exposed to high voltages and amperages (Zimmerman, 1993; *Naval Forces*, 1997). Besides advantages in strength, corrosion, and magnetic signature, lightweight construction, free shaping, and low maintenance have caused some countries to use fiber-reinforced plastics (FRP) for submarine components: covers for hydroacoustic systems (sonar windows); rudder for Germany's Type 212 submarine; and rudder and hydroplanes for Norway's U1a class submarines (vom Baur, 1995).

High speed is an important tactical-technical characteristic. But top speed is less important than top silent speed. Speed enables submarines to transit quickly to operating areas, to conduct rapid searches and attacks, and to escape quickly. More speed can be gotten by increasing power and/or decreasing drag. Nuclear reactors produce lots of power but submarine speeds have not increased proportionately because of the resistance of sea water. Efforts to reduce frictional drag are expected to focus on smooth fairing of the sail structure; smooth hull to obtain laminar flow in the boundary layer; and injection of minute polymers into the boundary layer around the hull (Zimmerman, 1993). As already indicated, a benefit from advances in periscopes, including the adoption of fiber optics and nonpenetrating optronic mast, is a smaller sail, which can be placed at an optimum location for reduction of noise and drag (*Naval Forces*, 1997).

Future submarine designs are expected to incorporate open architecture to accommodate technology insertion at any point in the development or operational life of the submarine. And a large percentage of combat systems—80 percent today—will continue to use COTS (commercial-off-the-shelf) equipment (Defense Science Board Task Force, 1998; Smith, 1999).

3. Sensors and Connectivity

All submarines emit some noise. Regular or continual noises are emitted by (1) mechanical vibration of rotating machinery transmitted to the hull, (2) the propeller, and (3) hydrodynamic flow. Occasional transient noise sources are opening of vents and torpedo tube bowcaps. The noise is emitted as continual broadband noise or a spectrum in which sources can be identified by spikes at fundamental or harmonic frequencies (Gates, 1987; Longworth, 1994). Hydrophones in passive broadband sonar systems will continue to be the primary means for detecting submarines. Broadband sonar processors examine the whole spectrum of incoming signals and separate noises, such as submarine flow noise, from random ocean noises that constitute the ambient noise level. Thus, passive sonar is used for initial detection of a submarine target and for analysis of its movement relative to the search platform. These systems include spherical bow arrays, flank arrays, and large-scale, wide-aperture towed arrays for open ocean operations. Improvements in minimum noise levels that could be detected make it possible to take advantage of the phenomenon of ocean convergence zone propagation to achieve detection out to 100 km or more. The advantages of towed arrays are so great that they are the primary detection means for submarines and for surface ASW escorts (Longworth, 1994).

We expect continued refinement of passive sonar systems to search for quieter submarines (Zimmerman, 1993; Defense Science Board Task Panel, 1998). In its examination of 21st century technology for submarines, the Naval Studies Board expects that hull designs will have embedded acoustic sensors replacing bow-mounted spherical array systems (Naval Studies Board, 1997). See Section 17 for more on sensors.

A primary focus of undersea research, development, test, and evaluation (RDT&E) will be the connectivity of all aspects of command, control, communications, and intelligence (C4I) without compromising stealth. This effort should lead to improving the submarine’s interoperability within a task force and/or with other elements of other naval or joint forces (Naval Studies Board, 1997; Zimmerman, 1993; Defense Science Board Task Force, 1998). Potential means for enhancing connectivity are laser communications (Naval Studies Board, 1997); buoyant cable antennas for two-way communications at depth (Corless, 2000); and an Internet-like, protocol-based, asynchronous, information-transfer system (Defense Science Board Task Force, 1998). In the Internet system, the submarine would choose the time delay between transfers. It remains to be seen whether these connectivity concepts will significantly improve underwater acoustic communications.

Because of spreading and attenuation, acoustic signal strength decays with distance from the source. The expansion of the acoustic wavefront as it propagates spreads the acoustic energy over a larger area, which reduces signal intensity. Attenuation involves absorption and scattering of acoustic signals by ocean water and suspended particles; attenuation losses grow with increasing frequency. A recent study of underwater acoustic communications indicated that “there is substantial agreement in the [acoustic communications] systems development community [that the combined effect of attenuation and source level was to define an approximate] maximum performance that can reasonably be expected of operational [acoustic communications] systems—even into the relativity far term. This boundary of performance is described by the equation:

$$[\text{Data rate in kilobits per second (kbps)}] \times [\text{Range in kilometers (km)}] = 100.$$

Thus, a 20-kbps communication would travel 5 km while a 2-kbps communication would travel 50 km (Sonalysts, 1998).

4. Payload

Submarines unconstrained by conventional (torpedo-tube centric) designs can include a variety of weapons, sensors, and off-board vehicles—UUVs and UAVs (unmanned air vehicles)—to extend the submarine’s battle space and reduce risk to the submarine (Naval Studies Board, 1997; Zimmerman, 1993; Defense Science Board Task Force, 1998). Weapons include torpedoes, mines, and missiles. Improvements in target location accuracy and weapon effectiveness could make land attack an increasingly important mission for submarines. A large number of land-attack missiles aboard these stealthy platforms might make the free-flooding cargo hold or other innovative weapon carrying concept(s) attractive architecture options for designing future SSNs and SSKs.

5. *Power Density*

Improvements in power density include the means to reduce power-plant weight and size. The reductions can be translated into better performance (speed), smaller noise signature, and improved hydrodynamic shaping (Naval Studies Board, 1997). We include all elements of the propulsion system. Nuclear-powered military submarines have mostly used PWRs for over 40 years (Zimmerman, 1993); we have not considered alternatives or advances in new nuclear plants.

In a nuclear-powered submarine, heat from the reactor core is turned into steam, which drives a turbine. The turbine turns an electricity-producing alternator, the output of which is connected to a motor that drives the propeller shaft—or, more commonly, the turbine is directly connected with gears to the propeller shaft (Zimmerman, 1993).

Nuclear propulsion eliminates the need for submarines to surface, where they are susceptible to detection and attack. Even with improvements in battery capacity and efficiency in the consumption of stored energy, diesel-electric submarines must surface to recharge their batteries. But AIP systems, using stored energy, eliminate the need to surface and give diesel-electric submarines the patrol endurance of nuclear submarines. AIP systems, however, do not appear to have the power density needed to drive a submarine very fast and very long. Only nuclear propulsion delivers high sustained speeds. We can expect that most diesel-electric submarines—besides those already equipped with AIP—will eventually have AIP.

The standard battery for submarines is still the inexpensive and robust lead-acid type (*Naval Forces*, 1997). The next most used in submarines is the nickel cadmium (NiCd) battery. Development of main batteries is expected to provide nickel-metal hydride (Ni-MH) batteries in the near term and lithium-ion (Li-ion) batteries after that (*Naval Forces*, 1995a). Energy densities are shown in Table 13.4-1.

Table 13.4-1. Specific Energies and Energy Densities of Various Battery Systems in Practical Values During a 5-hour Discharge Period

Battery	Watt-hours per kilogram	Watt-hours per liter
Lead acid	35	100
Nickel cadmium	30–40	80–130
Nickel metal hydride	60	175
Lithium ion	100	200

Source: *High Energy Batteries for the U212*, *Naval Forces*, June 1995.

PM motor technology is expected to enable PM motors to replace conventional motors in submarines. Conventional motors use electromagnets wound on the rotor; the use of PMs on the rotor eliminates the need to electrify it. The PM motors are more efficient, weigh less, and are more compact compared with conventional (wound-field synchronous and induction) motors (Zimmerman, 1993; Hollung, 1999; Integrated Power Systems, 2000). See Section 13.2 for more on motors.

One more technology that will likely be included in future submarine designs is the pumpjet, which utilizes more of the submarine’s propulsive power than a propeller. The pumpjet is essentially an axial turbine pump consisting of a duct or shroud surrounding a fixed stator with radial slots that twist the direction of water flow and a rotor with more blades than a conventional propeller. This cylinder arrangement, which was first used to maximize the energy supply of torpedoes, increases propulsive efficiency and lowers noise by reducing tip vortices. The pumpjet on the Navy’s Seawolf is both quieter and more efficient than an open propeller (Zimmerman, 1993; Scherr, 1996). The pumpjet is also discussed in Section 13.2 with an accompanying picture.

Besides submarines, three broad types of undersea vehicles can be distinguished: DSVs, ROVs, and AUVs. We do not cover tourist submarines, of which nearly 50 have been built or reconstructed; most of these accommodate a few dozen passengers. And we do not cover smaller manned submersibles designed for the leisure submarine market sector. Unmanned underwater vehicles (UUV) is the Navy's term for AUVs.[1] These are mobile, controlled, self-propelled, subsurface vehicles that carry sensors and tools. The above categorization is not absolute. For example, an untethered platform with high-level control via an acoustic data link to a supporting surface ship is not completely autonomous but it is classified as an AUV nevertheless (Marine Board, 1996).

Characteristics, functions, and some associated technologies of DSVs, ROVs, and AUVs are described below. We then discuss technologies by subsystems since the three types of undersea vehicles share many technologies. Table 13.4-2 identifies sources of technology transfer for the various subsystems.

Table 13.4-2. Technology Transfer

Vehicle Subsystem	Other Industries and Disciplines	Unique Requirements and Adaptations for Undersea Vehicles
Energy	Auto industry/electric cars, computers, and communications	Air independence, shipboard handling
Propulsion	Hydraulics, pumps, motors, valves, filters, plumbing, brushless DC motors, propellers	Hydrodynamics, pressure tolerance, ability to work in oil
Materials and Structures	Aerospace, boat building, aluminum composites, 316 SS, acrylics, graphite reinforced plastics	Pressure tolerance, corrosion resistance
Navigation and Positioning	Aerospace/compass and gyros, video cameras, lighting, GPS/inertial navigation system (INS)	Need to operate in acoustic rather than radio regime; GPS available only occasionally
Guidance and Mission Control	PC industry, automatic control	Unique hydrodynamics, long-term reliability
Data Processing	PC industry, object-oriented programming, computer-aided software engineering, computer science	Packaging for pressure housings, uniqueness of acoustic signal processing, pressure-tolerant electronics
Communications	Fiber optics, signal processing, electronics	Electromagnetic spectrum not available, acoustic medium only; packaging space restrictions
Task-Performance Systems and Tools	Construction, robotics, and automation	Moving platform and manipulator system, acoustic bandwidth, denser medium, high pressure
Sensors	Other ocean sciences, instrumentation, micromachinery, medical sensors	Seawater medium, long-term stability, biological fouling, corrosion
Launch and Recovery	Other marine applications, boat handling	Ability to work in multiple sea states, tether handling

Source: Marine Board, 1996.

B. DEEP SUBMERSIBLE VEHICLES

The DSVs are manned—generally a crew of three—vehicles that travel further vertically—from a few hundred meters to almost 6,500 m—than horizontally in their deep probe missions. They carry tools, sensors, and sampling devices for missions that generally do not exceed 16 hours. DSVs investigate the deep ocean when the investigation needs a trained observer; the vehicles perform various measurement, imaging, and sampling tasks after the dive target has been located by ships or unmanned vehicles. Because of its size, the DSV is a stable platform that supports viewing and manipulative tasks. Typical DSV operations involve many dives from a support ship without returning to port. Characteristics of DSVs are given in Table 13.4-3. The costs of manning, support systems, and

[1] In talking about unmanned submersible vehicles for commercial, scientific, or general military applications, reports and journals usually call them AUVs (autonomous underwater vehicles). Writings about these same vehicles for Navy applications generally use the Navy term UUVs (unmanned underwater vehicles).

insurance have made DSVs much more expensive to operate than ROVs (Marine Board, 1996; Rona, 1999; Jaeger, 1999).

C. REMOTELY OPERATED VEHICLES

The ROVs are unmanned, tethered vehicles. Power for its thrusters, cameras, and manipulators is delivered to ROVs—except for heavy work class vehicles—via an umbilical cable, which connects the vehicle to its operator on the surface. The cable is also used for the operator to pass commands to the ROV and for the vehicle to pass back data from sensing devices. These devices and the vehicle's manipulators enable the teleoperator to perform work on the sea floor. Because it has no life support system and no internal power source, the ROV is smaller than a manned submersible and has better underwater endurance. These characteristics enable ROVs to be operated from less expensive support ships. The ROV is constrained to operate near its support vessel because of the umbilical.

There are three classes of ROVs. First, there are small, low-cost vehicles used for shallow water inspection and work tasks. These may be small, portable TV cameras that weigh a few pounds. Second, there are light-work ROVs that perform a variety of tasks. And third, there are primary work-class vehicles that do most of the offshore work. While deeper diving ROVs carry minimal power plants and therefore need relatively small diameter umbilicals, heavy work-class ROVs carry 75–100 hp power plants for tasks at great depths. ROVs are used mainly for inspection and manipulation tasks in off-shore oil and gas operations and for laying undersea cables. Off-shore oil and gas exploration is now involving heavy work-class ROVs to perform tasks at depths of 3,000 m. Underwater search has generally involved towed ROVs (Marine Board, 1996; Ferguson, 1997–98; Wernli, 2000).

The size and weight of electro-hydraulic work-class ROVs have grown to such extent that it is difficult to find vessels with space to transport and support deep-water ROVs that perform heavy-work tasks. Until recently, the voltages required for servo-control of electric motors were too low for efficient transmission via the umbilical cable, and equipment to make the voltage conversion was too large and heavy for the ROV. The availability of power semiconductors that can operate at umbilical-compatible voltages now make it practical to make smaller, lighter voltage converters. The availability of these advanced, high-frequency converters, whose size and weight are about 20 percent of standard transformer units, make it feasible to produce commercial work-class ROVs (Michel, 1999). A new generation of electric ROVs with increased power density (compared with the older generation of electro-hydraulic vehicles) is expected to be lighter, less expensive, and require less maintenance (White, 1999). By eliminating the power conversion inefficiency associated with electro-hydraulic propulsion, the efficiency of electric power applied to the electric motor that spins the thruster blades is about 85 percent compared with 65 percent efficiency of mechanical power output at the thruster shaft following the electro-hydraulic conversion process. Electric propulsion also allows for simpler system design. Electro-hydraulic propulsion systems have more than 100 moving parts compared to less than 10 claimed by an electric work-class ROV manufacturer (Michel, 1999). Another major benefit of electric propulsion for deep-water operation is the decrease in umbilical cable weight: for a 3,000-m ROV, a typical electro-hydraulic work-class system requires 38,000 lb of umbilical cable; an electric system of equal performance needs only 16,000 lb. This reduction means substantial cost savings since umbilical cable weight is the primary factor in determining the size and weight of deck equipment on the support ship (Michel, 1999; White, 1999).

In discussing present and future capabilities of deep-water ROVs, these observations were made in a recent *Marine Technology Society Journal*:

- The offshore industry will focus on ROVs to work down to depths of 3,000 m for the immediate future. The technology is there when they need to go deeper.
- The military is focusing on shallow water mine-countermeasures and littoral intelligence, surveillance, and reconnaissance (ISR). Deeper water will remain a low priority.
- Vehicles will become simpler, and the equipment they mate and work with underwater will become more complex.

Table 13.4-3. Undersea Vehicle Characteristics

	DSVs	ROVs	AUVs
Definition	Untethered, human-occupied, free-swimming, undersea vehicle	Tethered, self-propelled vehicle with direct real-time control	Untethered undersea vehicle, may be totally pre-programmed and equipped with decision aids to operate autonomously; or operation may be monitored and revised by control instructions transmitted by a data link.
Depth	Many to 1,000 m Few to 3,000 m Very few to 6,000 m One to 6,500 m	Very many to 500 m Many to 2,000 m Few to 3,000 m Few to 6,000 m One to 11,000 m	Several to 1,000 m Few to 3,000 m Very few to 6,000 m
Endurance			
Time	Normally 8 hours, 24 to 72 hours max	Indefinite, depending on reliability and operator endurance	6 to 8 hours of propulsion* May sit on bottom for extended periods
Range	< 50 km	Limited in distance from host ship by tether	350 km demonstrated; near-term potential 1,500 km, depending on energy source
Payload	1 to 3 people, 45 to 450 kg (100 to 1,000 lb); adaptable to tools and sensors	45 to 1,590 kg (100–3,500 lb); adaptable to tools and sensors	11 to 45 kg (25 to 100 lb); adaptable to measuring equipment, tools, and sensors
Support			
Ship	Most DSVs require large ship support; ship size varies with DSV size	Depends on ROV size and mission requirements	Medium—depends on AUV size and mission requirements
Handling Systems	Depend on DSV size	Depends on ROV size	Similar to ROVs, depending on AUV size
Navigation Systems	Relative to seafloor or surface vessel	Relative to surface/seafloor	Seafloor and inertial navigation
Strengths	Direct human observation and manipulation	Real-time feedback to operator, long endurance capability, low cost per operating hour	Potential for automated operations, ability to operate with or without human command and without tether; minimum surface support
Limitations	Large size, weight, and cost due to manned requirements Limited mission time Potential personnel hazards	Tether cable potentially limits maneuverability and range	Energy supply Bandwidth of data link Capacity of internal recorders Limited work function complexity

* The Woods Hole Oceanographic Institute's ABE (Autonomous Benthia Explorer) has a proven propulsion endurance of 30 hours. The ABE's energy source was recently upgraded to lithium ion batteries (Bradley, 2000).

- Towed systems will continue to be a valuable asset for large-scale survey, but they will remain forever limited as “towed” systems.
- The cost of AUVs will continue to drop and their capability and acceptance will increase.
- On-board energy storage will increase along with computational power.
- Electric ROVs and work systems will reach maturity and increase in number.
- The requirement, and need, for deep ocean exploration and research will increase (Wernli, 1999, p. 37).

The Navy operates the AN/SLQ-48(V) Mine Neutralization System (MNS), an ROV, shown in Figure 13.4-1. This unmanned mine-hunting submersible, which is carried by the MCM-1 and MHC-1 class vessels, is described below by the U.S. Naval Mine Warfare Plan (2000):

> The vehicle obtains its power and guidance commands from the launching ship through a 3,500-ft umbilical cable. After a target is detected and classified by the ship’s sonar, the MNS, which is initially directed by ship’s sonar data, proceeds to the target at speeds up to 6 knots. The vehicle carries a small, high-definition sonar and an acoustic transponder that enables the vehicle to be tracked by the shipboard sonar. There is also a low-light-level television for examining the target, with illumination provided by onboard floodlights. Propulsion is provided by two 15-hp hydraulic motors, and there are two horizontal and two vertical hydraulic thrusters for the exact positioning of ordnance to the target. Two consoles on board the ship monitor and control the vehicle’s operation. The MNS can destroy bottom mines by placing an explosive charge near the mine or by cutting the cable of moored mines, causing them to rise to the surface for subsequent neutralization or exploitation (p. 65).

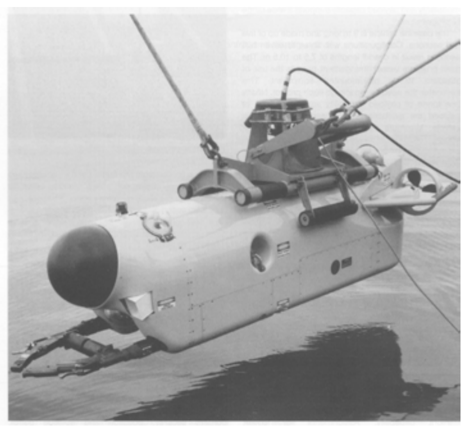

Figure 13.4-1. SLQ-48(V) MNS (Source: U.S. Navy)

Mine hunting is done mostly by ROVs. Some modern mines can be programmed to destroy a nearby ROV. Deploying and recovering an ROV with a mine disposal charge takes 30–45 minutes, and the ROV must be recovered before the mine is detonated. Because of size limits, MCM vessels carry only two ROVs (Foxwell, 1998). Replacement of ROVs by UUVs and expendable mine disposal means for MCM operations is ongoing. Use of UUVs reduces mission time, cost, and operational vulnerability.

In the commercial world, the economics of ROVs vs. UUVs will bring UUVs into wide use for offshore oil and gas exploration and development. A recent Shell oil company analysis showed a $100M saving over 5 years by using AUVs (International Ocean Systems, 2000).

D. UNMANNED UNDERWATER VEHICLES

The UUVs are unmanned submersibles that carry their own prime power. Their onboard computers can execute entire missions with instructions programmed by their controllers before launch. Or they may be fitted with a fiber-optic cable over which data can be sent to a remote controller, who can transmit instructions. Since it does not have an umbilical, the UUV is able to operate at relatively long distances from its support ship. Missions for

UUVs include military ISR and searching, surveying, data gathering, and laying fiber-optic cable for nonmilitary users. MCM is a top priority for naval forces.

1. Mine Countermeasures

Sea mines have long been a threat to shipping. They will continue to be an open ocean threat, and they will be especially troublesome as the military focus shifts to maritime operations in littoral areas. An overview of the mine threat from the U.S. Naval Mine Warfare Plan (2000) is given below.

> The mine's ability to function as a force multiplier (whether real or perceived), combined with its cost effectiveness and ease of deployment, make it a highly sought after naval weapon whose effectiveness has not been compromised. Since the beginning of the Cold War, at least 14 U.S. ships, including 2 in the last decade alone, have been damaged or sunk by mines during relatively small-scale mining operations. Four dated, low-technology mines—two of which were simple moored contact mines—caused hundreds of millions of dollars in damage to U.S. warships during both the Gulf Tanker War of the late 1980's and the 1991 Gulf War, and cost multinational forces tens of millions of dollars to counter them. In 1988, in the most serious incident, *Samuel B. Roberts* (FFG-58) nearly sank after striking an Iranian SADAF-02 contact mine, estimated to cost $1,500, causing nearly $96 million in damages.
>
> Today the Navy can expect to encounter a wide spectrum of naval mines, from traditional low-technology mines to technology advanced systems. Although low-technology mines continue to be manufactured, today's mine producers and exporters are focusing on the growing demand for more capable weapons. Modern influence mines, whether magnetic, acoustic, seismic, underwater electric potential (UEP), pressure, or any combination thereof, may incorporate advanced technologies to improve their lethality, reliability, and versatility.

The mine warfare environment is divided into the five depth regimes identified below and illustrated in Figure 13.4-2 (U.S. Naval Mine Warfare Plan, 2000).

- *Deep water*—waters deeper than 300 feet. Mines in the deep water zone are generally rising or moored types, although there are some deep water bottom mines.
- *Shallow water*—waters between 40 and 300 ft deep. This zone typically has bottom, moored, and rising mines.
- *Very shallow water zone*—waters from 10 to 40 ft deep. Mines in the very shallow water zone typically include bottom, moored, controlled, and buried types.
- *Surf zone*—waters less than 10 feet deep to the beach. The surf zone generally has anti-invasion mines, controlled mines, buried mines, and other obstacles.

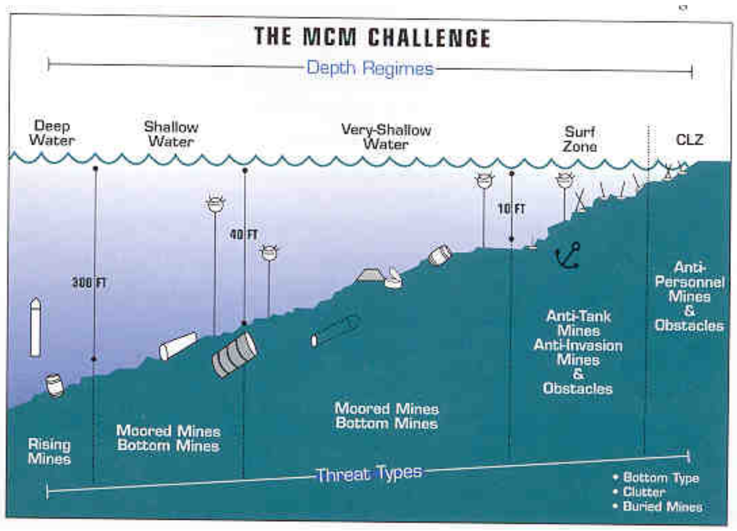

Figure 13.4-2. Mine Warfare Environment. (Source: U.S. Naval Mine Warfare Plan, 2000)

- *Craft landing zone*—the beach itself. The threats faced are generally similar to those in the surf zone, with the addition of conventional land mines (p. 89).

The mine threat to amphibious power projection has motivated an examination of the requirements for effective and efficient mine reconnaissance, avoidance, classification, and neutralization. UUVs have emerged from that examination as important vehicles that reduce risk to MCM vessels, other surface ships, or submarines. With UUVs, the mine detection and classification process can be accomplished well ahead of its mother ship and the open-ocean or amphibious force of which it is an organic member (Scott and Hewish, 1999).

E. SUBSYSTEMS OF DSVs, ROVs, AND AUVs

Technologies, some of which have been covered above, are discussed below by subsystem—energy, propulsion, materials and structures, navigation and positioning, guidance and control, data processing, communications, payload (including work systems and sensors), and launch and recovery.

1. Energy

As in the case of batteries for diesel-electric submarines, high-energy-density sources are sought for DSVs and AUVs. Factors influencing battery selection include power density, outgassing properties, failure modes, reliability, number of recharge cycles, operability over a broad range of temperatures and pressures, and cost. Energy limitations on AUVs are critical, and new energy sources are being sought. Higher energy systems are important for high-endurance AUVs such as the Navy's Long-Term Mine Reconnaissance System (LMRS). Current battery types in AUVs include lead acid, nickel-cadmium, silver zinc, and lithium thionyl chloride, which is the LMRS's high energy density, nonrechargeable energy source. Table 13.4-4 contains performance data collected by the National Research Council's Marine Board on available energy sources. Since most R&D in the energy storage field occurs outside the area of undersea vehicles, near-term DSV and AUV applications will be met by existing battery chemistries (Marine Board, 1996). With the development of fuel cells, AUV designs should be expected to be renewable vice rechargeable (which implies battery) energy sources.

An interesting concept that could be applicable to some AUV missions involves a seafloor grid system with nodes at which AUVs can dock for battery recharging and data downloading (Robinson, 1999). See Section 13.2 and Section 7 for more on energy systems.

2. Propulsion

Since the 1996 Marine Board study of future national needs for undersea vehicles, electric drive and pumpjet propulsors have emerged as significant advances for ROVs and AUVs, respectively. As already discussed, electric drive increases the power density, reduces the umbilical cable weight, and enhances the supportability of work-class ROVs. The advantages of the pumpjet, increased propulsive efficiency and less emitted noise, were identified in the discussion of submarines. The Marine Board considered propulsion systems a mature technology, and it foresaw a low priority for development "over the next few years."

3. Materials and Structures

Structural materials used for undersea vehicles—DSVs, ROVs, and AUVs—have been adapted from submarine, shipbuilding, and advanced aerospace industries. Although materials and structural designs for ROVs and AUVs are relatively mature, improvements in materials are more important for DSVs, which require strength to counter high pressures (Marine Board, 1996). Materials and processing technology in Section 14 apply to all types of marine vehicles.

4. Navigation and Positioning

Table 13.4-5, which is developed from tables in Section 16, shows recent navigation and positioning accuracy data for systems available to DSVs, ROVs, and AUVs. For work in a localized area, position accuracies of 1 m at frequencies of 26 to 30 kHz are achievable with bottom-placed transducers in a long baseline network of acoustic transponders up to 4 km apart (Marine Board, 1996).

Table 13.4-4. Performance Characteristics of Available Energy Sources*

	ASSESSMENT OF ENERGY TECHNOLOGIES FOR USVs					
Technology	**Specific Energy W-h/kg**	**Energy Density Wh/Liter**	**Cycle Life**	**Cost $/kW-h**	**Maturity for Undersea Vehicles**	**Safety Concerns**
SECONDARY BATTERIES**						
Lead Acid (Pb/Pb0)	35	90	800	50	Proven	H generation
Nickel Cadmium (NiCd)	55	130	1,000	1,500	Proven	Cd toxicity
Nickel Hydride (NiH_2)	60	150	10,000	2,000	Proven	High pressure H
Nickel Metal Hydride (NiMH)	70	175	300	50	Proven	High pressure venting
Silver Zinc (Ag-Zn)	140	380	20	1,000	Proven	H generation
Silver Iron (Ag-Fe)	150	200	200+	500–800	Demo	H generation
Li-Solid Polymer Electrolyte (LiSPE)	150	360	200	100–1,000	Lab	Lithium fire
Lithium Ion Solid State (Li-Ion-ÍPE)	150	360	1,000	100–1,000	Lab	None
Lithium Ion (Li-Ion)	200	200	2,000	500–1,000	Proven	Venting
Lithium Cobalt Dioxide ($LiCoO_2$)	220	300	50	1,000	Lab	Pressure venting, Li fire
PRIMARY BATTERIES**						
Lithium Sulfur Oxide ($LiSO_2$)	140	500	1	400	Demo	Li fire
Silver Zinc (Ag-Zn)	220	400	5	3,000	Demo	H generation
Lithium Manganese Dioxide ($LiMnO_2$)	400	450	1	200	Proven	Li fire
Aluminum-Seawater	450	400	1	100	Demo	N/A
Lithium Thionyl Chloride ($LiSOCl_2$)	480	500	1	300	Demo	Thermal runaway
Lithium Carbon Monofluoride ($Li(CF)_x$)	800	1,200	1	1,700	Proven	Li fire
FUEL CELLS						
Alkaline	100	90	400	5,000	Demo	Gaseous H and O fires
Proton Exchange Membrane (PEM/GOX/GH)	225	200	50	10,000	Demo	Gas H and O fire
Proton Exchange Membrane (PEM/LOX/LH)	450	400	50	15,000	Lab	H and O fires
Proton Exchange Membrane (PEM/SOX/SH)	1,000	883	50	5,000	Lab	N/A
Aluminum-Water Semi-cell ($Al/H_2O/LOX$)	1,200	800	1	10,000	Demo	H and O fire
HEAT ENGINES (Closed-Cycle, Air-Independent Propulsion Systems)						
Internal Combustion Engine	75	170	2,000	50–100	Demo	Fuel fire
Diesel Engine	125	75	1,000	100–200	Demo	Fuel fire
Brayton-Lithium Sulfur Hexafluoride ($LiSF_6$)	400	700	1	15	Demo	Fuel fire
Stirling	200	250	2,000	50–100	Proven	Fuel fire

* Source: Marine Board, 1996.

** Battery parameters are based upon single cells; non-battery performance parameters are system level.

Table 13.4-5. Navigation Systems Accuracy*
(Source: Tables 16.1-1 and 16.3-1 in Section 16)

	Inertial Navigation System (INS)	**Global Positioning System (GPS)**	**Doppler**	**Data Based Reference Navigation**
Alone	0.8 nm/hr CEP	16 m CEP	0.5% of distance traveled	30 m CEP
Hybridized with INS	na	10 m SEP	0.3 nmi/hr CEP	5 m CEP
Hybridized with GPS	10 m CEP	na	5 m CEP	6 m CEP

* Note: CEP = circular error probable; SEP = spherical error probable.

5. *Guidance and Control*

The Marine Board (1996) describes the general design of current guidance and control and identifies the direction of future development. With advances in automation theory, direct control of all functions of an undersea vehicle by a human operator is being replaced by "supervisory control" involving high-level, task-oriented commands. These automation advances together with developments in navigation and sensors will enhance the capabilities of ROVs and, especially, AUVs, which will be capable of pursuing tasks with abstract descriptions such as surveying an area and, based on changing internal and external factors, replan and reconfigure the vehicle's mission.

Guidance and control functions of undersea vehicles generally use a layered architecture. At the higher functional level, guidance involves mission management activities, such as planning and directing vehicle movement. At the lower level, control interacts with equipment—receives guidance orders and commands physical actuators, propulsors, and effectors—on the vehicle to provide stable, controlled operation of the vehicle.

Navigation, guidance, and control functions are interactive, and they use many common sensors and processors. Improvements in navigation and control technologies now permit automation of all vehicle motions, such as long-period hovering and following a preplanned track line with a human operator providing high-level, task-oriented commands but not directly controlling all vehicle functions. Guidance and control improvements for subsurface vehicles, especially AUVs, are expected to progress from simple way-point control to enable the vehicle to perform more abstractly described tasks.

6. *Data Processing*

Two types of data processing, payload and vehicle management, are described by the Marine Board (1996):

> The payload processor collects, processes, compresses, and records the data produced by the vehicle and its sensors, often on disk in the vehicle itself or on a support vessel. The data are generally recorded during operations and processed afterward, especially in scientific applications. Data compression is essential when recording devices or the uplink bandwidth [is] limited and data volumes are large. The payload processor also can perform processing to augment and fuse the data that are collected; for example, the vehicle data can be matched to the image from a sonar, and the fused result gives an accurate picture of the situation encountered by the vehicle at a given time and place. The advent of fiber-optic communications and advanced sensors for ROVs has allowed transmission of large volumes of data up the tether for data logging, management, and display….
>
> The vehicle-management computer typically performs all the housekeeping functions necessary to keep the vehicle in motion along the prescribed path. The data can be used to control vehicle [components] such as thrusters, control surfaces, valves, and manipulators in real time. As the human operator becomes more removed from the vehicle control loop, and as tasks become more automated, the performance of vehicle-management computers becomes critical to mission success (p. 33).

Data processing is also involved in detecting a failed or faulty sensor and in calibrating sensors used for making measurements. Improvements in the capabilities of undersea vehicles are closely related to advancements in microprocessors and computer science. Section 10 covers these technology advances as well as developments in data preparation, fusion, presentation, and analysis. Undersea vehicles require fusion of sonar data, video, still images, water column measurements, and vehicle position data.

7. *Communications*

Communications between human operators and undersea vehicles involve control signals, mission status reports, and sensor data. Generally, ROVs use umbilical cables that contain coated, shielded, twisted-pair copper or, more and more commonly today, fiber-optic cable, which has greatly increased the capability of ROVs to transmit large volumes of data for logging, management, and display. Tethers of twisted wire pairs of 1,000 m or less can accommodate ROV video and data channels whose transmission rates are greater than 1 MB/sec. Tethers of optical fibers, which greatly exceed coaxial cable performance, are used for very long distances or high transmission rates. Multimode fiber-optics are used today for tether lengths of 1,000 m to 3,000 m, and single-mode fiber-optics are used for longer tethers. In the future, single-mode fiber-optics are expected to be used in all lengths. The AUVs generally transmit acoustically through water at frequencies of 8.075 kHz and 27 kHz (Marine Board, 1996).

Communications between AUVs will be vital for networked, distributed sensor fields for submarine detection, mine hunting, and search related to ocean salvage operations. As already discussed in the submarine part of this section, the underwater acoustic transmission is expected to be limited for the foreseeable future by

$$(\text{data rate in kbps}) \times (\text{range in km}) = 100.$$

Thus, for example, 1 kbps can be transmitted 100 km or 10 kbps can be sent 10 km.

8. Payload: Work Systems

Robotic manipulators are used by DSVs and ROVs to accomplish military, industrial, and scientific tasks. Figure 13.4-3 shows a manipulator mounted on the forward, port side platform of the Navy's CURV III, a deep-sea-recovery ROV. Manipulator use on AUVs is embryonic, and much R&D is needed in order for AUVs to be able to perform more than simple tasks. The Marine Board described current manipulator use and new control techniques as follows (Marine Board, 1996):

> Current practice involves rate or master-slave manipulators, where the operator (located inside a DSV or on a surface vessel controlling an ROV) operates the arm by throwing switches or by moving a miniature version (the "master") of the manipulator on the vehicle (the "slave"). Typically, modern hydraulic arms on large ROVs can lift hundreds of kilograms, even when fully extended (p. 36).
>
> New control techniques drawn from space developments will allow the human operator to command directly at the task level what is to be done with the object of interest, and the vehicle-manipulator system will respond by carrying out that command. The operator needs no special "crane operator" skills, and a scientist or the field engineer can play the operator role. The operator can then focus completely, in real time, on the task itself and the objects to be manipulated (p. 36).

Manipulators use "end-effectors" to perform actual tasks. These end-effector devices are general-purpose hands or grippers and special-purpose power tools (drills, cutters) or wrenches (for offshore oil work for example). The development of new underwater sensors for proximity, force, touch, and audio would give the operator feedback on the performance of manipulators and other mechanical systems. These developments will likely be based on devices for terrestrial and space applications.

Figure 13.4-3. CURV Recovery ROV (Source: U.S. Navy)

9. Payload: Sensors

Undersea vehicles collect data from various types of sensors, which are generally the technology driver or limiter for vehicle applications. In the context of "payloads," sensors are those that collect data from external sources and not that related to vehicle functioning. The Marine Board (1996) says

Such sensors can be carried by all classes of vehicles; typically, the sensors are matched to the type of host vehicle that is transporting and supporting them. For example, sensors that are applicable to large area searches would not normally be installed on DSVs, which may have poor range and endurance capabilities. Furthermore, the characteristics of specific vehicle types can have a significant influence on the design of sensors. A case in point is AUVs, where sensors are critical to overall capability, particularly because of limitations to direct interaction by humans in system control. From a handling and cost point of view, a common desire is to make AUVs as small as possible, thus imposing payload-carrying-capacity and resident-energy limitations. This, in turn, imposes similar restrictions on allowable sensors, which must be smaller and more energy efficient. If AUVs make possible longer missions than those of DSVs and ROVs, they will need sensors that are more resistant to fouling and with longer lasting calibration characteristics. DSVs and ROVs will derive benefits from improvements in these same sensor characteristics.

a. Acoustic Sensors

Whereas ASW uses passive low-frequency sonar for the long-range detection problem, minehunting and other underwater search operations use active high-frequency sonar to obtain high-definition images of small objects. High-frequency sonar systems are limited to ranges of about 100 m, which is within the danger zone (about 200 m from the mine) of many modern mines (Watts, 1999). Synthetic aperture sonars are reported to resolve a 50-mm object at 180 m (Scott, 1999). Imaging sonar performance is severely reduced in shallow waters.

b. Optical Sensors

Absorption and scattering in water severely limit the range performance of optical images, which do provide high-resolution capability. Even in clear water, optical methods using floodlights or flashlamps with photographic, SIT (silicon-intensified target), or charge-coupled device cameras provide very limited working distances. Development of laser-based underwater imaging has used properties of a laser source to mitigate the effects of absorption and scattering. Laser line scanners (LLS) and range-gated laser imagers have direct applicability for work by DSVs, ROVs, and AUVs. Range performance is generally measured in terms of water beam attenuation length L, which is defined as $1/e$. Operational laser range gate underwater imaging systems can image identifiable targets at 6 L and can detect targets at 10 L. By comparison, underwater video systems can achieve range performance of 2 L (Smolka, 1994).

10. Launch and Recovery

Techniques are currently adequate for launching and recovering DSVs and ROVs by surface ships, semi-submersibles, and platforms. Large ROV launch and recovery systems have a motion-compensation and tether-compliance component to limit the effect of sea surface motion on the vehicle. The evolution in this area will involve reducing size so that smaller, less costly surface support vessels can be used. Techniques for launching and recovering AUVs from submarines are evolving (Marine Board, 1996). The Navy will surely examine techniques for submarine recovery of AUVs in fewer than the currently estimated 30 minutes.

11. Current Capabilities

In its assessment of notional needs for the performance of undersea work tasks, the Marine Board evaluated current undersea vehicle (DSV, ROV, and AUV) abilities to perform the functions listed in Table 13.4-6.

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LIST OF TECHNOLOGY DATASHEETS
13.4. UNDERSEA VEHICLES

DATA SHEET 13.4. ELECTRIC ROV

Developing Critical Technology Parameter(s)	Size, weight, maintainability, and supportability of electric ROVs relative to today's electro-hydraulic ROVs.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	All ROV users will opt for a new generation of electric ROVs.
Affordability	Electric ROVs will provide a direct cost avoidance resulting from being smaller, lighter vehicles that require less maintenance. An indirect cost avoidance will be realized by the need for smaller, much lighter umbilical cables to transfer energy to the ROVs.

BACKGROUND

Electric ROVs will have about 10 moving parts in the propulsion systems compared with over 100 in present electro-hydraulic systems for work-class ROVs. Besides simpler design, the electric ROVs will be smaller, lighter, and more energy efficient and will require less maintenance. Another major benefit of electric propulsion for deep-water ROV operations is the decrease in umbilical cable weight. For a 3,000-m ROV, a typical electro-hydraulic work-class system requires 38,000 lb of umbilical cable; an electric system having the same performance needs a 16,000-lb cable. The umbilical savings in weight and cost could in turn reduce the size and weight of deck equipment on the ROV support ship.

DATA SHEET 13.4. UUV NETWORKS

Developing Critical Technology Parameter(s)	Autonomous or semi-autonomous networked UUVs for minefield reconnaissance.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms for mine detection and classification.
Major Commercial Applications	A nonmilitary use of networked UUVs is 3–D synoptic sensing of the ocean environment; the UUVs would continuously measure temperature, conductivity, depth, sound speed, dissolved oxygen, chlorophyll concentrations, etc., and collect water samples.
Affordability	None identified.

SECTION 13.5—ADVANCED HULL FORMS

Highlights

- Principal performance goal is increased speed.
- Evolutionary technology advances in speed, endurance, seakeeping, and stealth are expected to produce evolutionary gains in mission effectiveness, survivability, and affordability.
- Less vulnerability to underwater explosions, compared with monohulls, makes ACV and SES hull forms candidates for the mine countermeasure mission, for which the UUV (Section 13.4) is also a candidate.
- Fast ferry (passengers, cars, freight) industry will continue to grow as the commercial market presses for higher speeds.
- Speed and economic advantage favor catamaran hull form for maritime transport for speeds up to about 50 knots. The trimaran may turn out to be the best multihull solution in this speed range. Other hull forms might be favored for some maritime transport routes.

***OVERVIEW*[1]**

This group of technologies and hardware is related to advanced hull forms, which represent a small fraction of both naval and commercial ships in service. Much of the discussion of these unconventional hull forms is from a relatively old, but not outdated, publication of the American Society of Naval Engineers (Gore, 1985). Most seagoing tonnage of the world consists of "displacement craft," of which monohulls have attributes that make them the most widely used hull forms:

- Transport;
- Small propulsion power requirements and long endurance at low speeds and moderate propulsion power at moderate speeds;
- Ruggedness, simplicity, and durability;
- Tolerance to growth in weight and displacement;
- Existing infrastructure of yards, docks, and support facilities is designed for monohulls; and
- Low cost.

Together, these characteristics describe affordable ships that can carry large payloads of any composition over great distances at low to moderate speeds (less than about 25 knots) and with good mission endurance when away for long periods of time from home ports. The ships have shortcomings that we have learned to live with. The shortcomings include small deck areas; unfavorable lateral stability characteristics, particularly for high-performance slender monohulls; and poor seakeeping in head seas and beam seas. Because they operate at the water surface, monohulls are also characterized by limited speed and by sensitivity to sea state (Graham, 1985). Sea-state definitions are contained in Table 13.5-1. The above limitations have led to the development of the following non-monohull forms, which generally offer higher speeds and greater stability in certain operating conditions than conventional monohulls:

- Surface effects vehicles, which include ACVs and SESs;
- Hydrofoils;
- Small waterplane area twin hull (SWATH) ships;

[1] The sources of most of the material in this subsection are identified by the list of references.

- Catamarans, trimarans, or other multihull forms; and
- Hybrid combinations.

Table 13.5-1. Sea State, Wave Height, and Wind Speed
(Source: *Principles of Naval Architecture*)

Sea State Number	Range of Significant Wave Height (m)	Range of Sustained Wind Speed (knots)
	Range	Range
0–1	0–0.1	0–6
2	0.1–0.5	7–10
3	0.5–1.25	11–16
4	1.25–2.5	17–21
5	2.5–4	22–27
6	4–6	28–47
7	6–9	48–55
8	9–14	56–63
>8	>14	>63

Sketches of various hull forms are shown in Figure 13.5-1. Besides the monohull, other displacement craft that depend largely on buoyancy support are the catamarans, trimarans, and SWATHs. By utilizing powered lift (ACV, SES) or dynamic lift (hydrofoil), advanced hull forms can provide higher speeds—by reducing or nearly eliminating either the wave-making resistance or the hull surface frictional resistance—and better stability at high speed than monohulls, which depend on static lift, which comes from the buoyancy force acting on the vessel. For some missions, buoyancy support for monohulls can be supplemented by dynamic lift provided by a planing hull design.

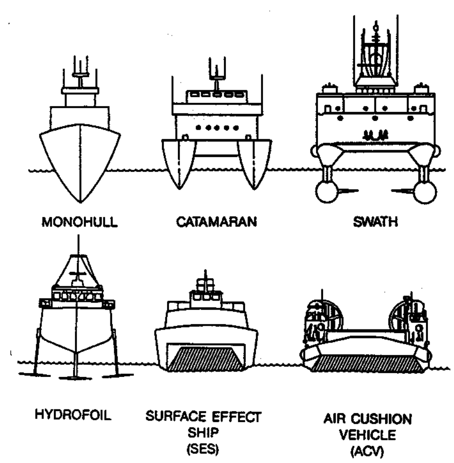

Figure 13.5-1. Advanced Hull Forms
(Source: Drawing by William Clipson in Polmar, 1993)

Advanced hull forms typically comprise various technologies—propulsion, propulsors (propellers and water-jets), lightweight structure, lightweight armor, hydrodynamics (affecting hull-propulsor interactions, propulsor performance, and support forces acting on the vessel's lower surfaces), and vehicle control. Embedded in a total system, these technologies provide speed, seakeeping (pitch and roll stability in all weather over a wide range of speeds), and other performance capabilities not obtainable with monohull designs. Of course, each advanced hull form design has its operational disadvantages which limit its suitability to certain missions.

A. ACV

The ACV rides on a cushion of relatively low pressure air, the escape of which is impeded by a flexible fabric skirt attached around the periphery of the underside of the craft's hard structure. Air must be supplied continuously to the cushion using fans or blowers housed within the hard structure to maintain the supporting pressure over the broad base of the craft as air escapes beneath the flexible skirt. In this way, the hard structure can ride well above the surface of the sea or land while the flexible skirt offers very little resistance to forward motion. Calm-water speeds in excess of 80 knots have been demonstrated since the early 1960's. Its high speed makes the ACV useful for the fast-attack mission, and its amphibious nature gives it an over-the-beach assault capability. Since its hull is not in contact with the water, it is less susceptible to damage by mine explosion. Consequently, the ACV has potential for mine hunting. The ACV performs as well as monohulls in moderate sea states. Figure 13.5-2 shows a landing craft air cushion (LCAC) vehicle.

Figure 13.5-2. LCAC Vehicle
(Source: U.S. Navy)

B. SES

The SES, like the ACV, uses a pressurized air cushion to reduce resistance to motion. But unlike the ACV, the SES has rigid catamaran-style sidehulls. When air cushion pressure raises the craft, its sidehulls remain slightly immersed to contain the air cushion. Flexible skirts fore and aft allow waves to pass through the cushion area. The sidehulls enhance the underway stability and maneuverability of the SES. Figure 13.5-3 illustrates the air-cushion principle of ACV and SES operation. An SES is shown in Figure 13.5-4. High speed and improved seakeeping make the SES also a candidate for the fast-attack mission. Like the ACV, the SES is less susceptible to under-the-keel attack by mine explosion than a monohull and thus is also attractive for mine hunting. Numerous SESs are commercially successful as fast passenger and car ferries. And like the ACV, the SES has to carry extra machinery (compared with other vessels) to generate air to feed the cushion. This increases weight and power consumption that is offset at high speeds (greater than about 50 knots) due to reduced resistance to forward motion (compared to a monohull).

C. HYDROFOIL

The hydrofoil supports itself primarily by lift generated by water passing around foils (wings) under water (see Figure 13.5-5). Two basic foil system types are used for hydrofoil craft: (1) surface-piercing V-shaped or U-shaped foils and (2) fully submerged foils (see Figure 13.5-6). The hull of the craft can be lifted out of the water completely at foilborne speeds. The higher the speed, the greater the lift, which can be controlled by changing the foils' angle of attack. Speeds are usually in the 40- to 50-knot range, although top speeds have approached 100 knots with use of supercavitating foil sections. As the hydrofoil slows below take-off speed, the foils no longer provide adequate lift, and the craft sinks onto the sea surface. The size of the foils required to lift a hydrofoil vessel's hull completely out

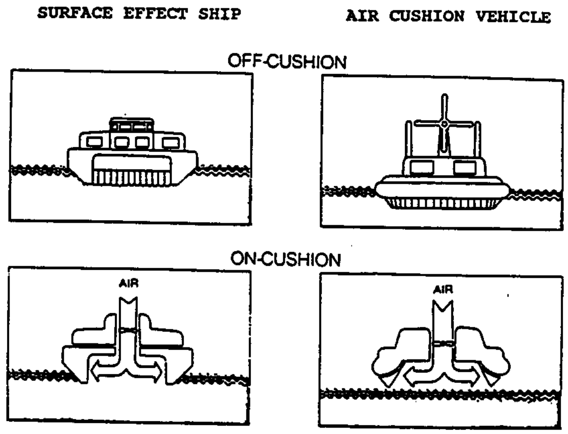

Figure 13.5-3. The SES/ACV Principle
(Source: Rolfe, 1990)

Figure 13.5-4. SES-100B Surface Effect Ship. A 100-ton displacement SES with 91-knot speed capability. (Source: Polmar, 1993)

Figure 13.5-5. Vector Forces on Hydrofoil Craft
(Source: Gillmer, 1970)

of the water for foilborne operation puts a practical limitation on the overall size of hydrofoil vessels. The scale size and weight of the foils grows disproportionately with increases in the hydrofoil vessel's displacement. As a consequence, in practice, hydrofoil vessels have been effectively limited to about 500 tons in displacement. In the commercial sector, hydrofoil vessels have been used extensively to transport passengers, as have ACV, SES, and catamaran vessels. High speed plus the ability to operate in rough water make the hydrofoil ideal for the fast-attack role in restricted waters.

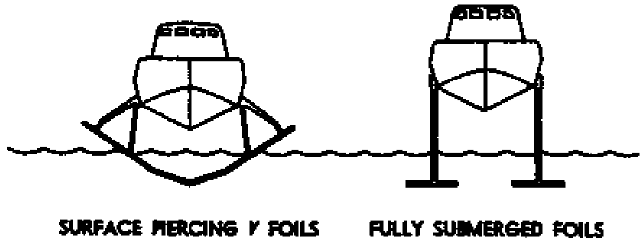

Figure 13.5-6. Foil Arrangements of Hydrofoil Craft
(Source: Gillmer, 1970)

D. SWATH

The SWATH usually has a pair of fully submerged hulls on which slender struts are mounted to support a cross structure. The struts present minimal waterplane area so that deeper immersion of the hulls causes a small increase in buoyancy. Designing the struts with appropriate water plane properties is the key to good seakeeping. In addition to having better seakeeping quality than comparable monohull vessels, a SWATH exhibits less falloff in speed with increasing sea state. Excellent seakeeping qualities, large deck area, and an ability to accommodate current and future weapons by trading off fuel capacity to maintain a constant, full-load displacement make SWATH another surface-attack threat, albeit not as fast as the hydrofoil, ACV, SES, or catamaran.

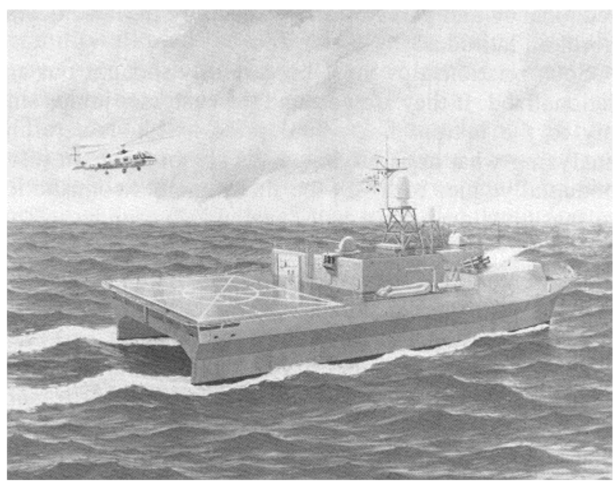

Figure 13.5-7. Notional Fix-Type SWATH Ship: Artist's Rendering
(Source: Gore, 1985)

"Slice," a SWATH derivative with four short hulls, or pods, instead of the SWATH's two long hulls was recently developed under a joint Office of Naval Research (ONR)-industry program (see Figure 13.5-8). Propulsors are located in the forward pods. The four-pod design significantly reduces wave-making resistance. Claimed advantages over a conventional monohull are higher speed for the same power; lower installed power and fuel consumption for the same speed; more flexibility in strut/hulls arrangement; and lower wake signature at high speed (Foxwell, 1998). However, the Slice concept is under evaluation and its various merits have not yet been proven.

E. CATAMARAN

The catamaran is a vessel with two hulls—normally arranged parallel and abreast—separated from each other but attached to a common deck. The distribution of displacement between the two hulls allows the individual hulls to operate with less wave-making resistance at higher speed-length ratios, although this is offset somewhat by increased wetted area and increased frictional resistance. These vessels have been demonstrated commercially to exhibit better performance than monohulls in a speed range of 35 to 40 knots, depending on size. Two hulls provide

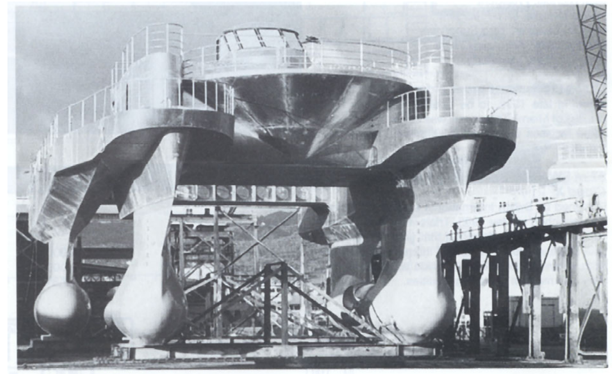

Figure 13.5-8. Top and Bottom Views of Slice
(Source: Office of Naval Research and Lockheed Martin)

an obvious gain in initial stability. Suitable missions include submarine rescue and oceanographic research. Although catamarans are increasingly popular as commercial ferries in restricted or coastal waters, their seakeeping quality is inferior to that of the SES and the small waterplane area ship (SWAS), which limits their potential for open-sea operations. That potential should be mitigated for a three-hull vessel, trimaran, which will undergo sea trials later this year in the UK.

F. HYBRID

The SES, which uses powered aerostatic lift to supplement hydrostatic lift from buoyancy, is a hybrid hull form. Another noteworthy hybrid is the hydrofoil small waterplane area ship (HYSWAS), which uses dynamic lift generated by hydrofoils to supplement buoyancy support. A HYSWAS design in Figure 13.5-9 shows a long central strut connecting the center of the upper SWAS hull to a lower hull on which hydrofoils are mounted. Tests of a 27-ft HYSWAS research vessel have revealed several advantages: (1) much less roll, pitch, and heave compared with a monohull; (2) better hydrodynamic efficiency than for a monohull above 20 knots; (3) reduced drag and power hump compared with pure hydrofoil vessels; (4) very little wake; and (5) hydrodynamic and propulsive efficiencies that reduce fuel consumption and extend range over comparable monohulls (Maritime Defence, 1997). The only limitation is the vessel's large draft. Success in an at-sea demonstration of the 27-foot version could lead to a Navy development of a much larger vessel as the next step in assessing the potential of HYSWAS.

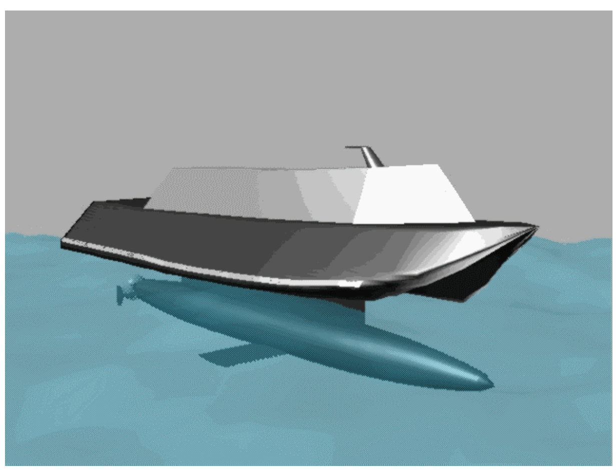

Figure 13.5-9. HYSWAS Design of a Patrol Combatant
(Source: Maritime Applied Physics Corporation)

G. HIGH SPEED MONOHULLS

The advantages of conventional monohulls attract R&D activity to increase speed, range, and carrying capacity and to reduce cost. Displacement monohulls also have limitations: limited top speed and sensitivity to sea state since they operate at the water surface. Wavemaking resistance can be expected to limit displacement monohull vessels to an upper practical limit of 40 knots (Graham, 1985).

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SECTION 13.6—HUMAN SYSTEMS INTEGRATION

Highlights

- Personnel costs are the dominant cost drivers of operating and supporting ships during their lifetime.
- System designs must take into account the abilities in which humans surpass machines and vice versa. This leads to optimal manning.
- Task performance by humans can be measurably improved and workload reduced by paying attention during the system design to the ergonomics of displays, controls, communications, procedures, and workplace layout.

OVERVIEW[1]

The major ownership cost of ships is incurred in operating and supporting them during their lifetimes. The dominant cost driver is personnel. Systems onboard Navy surface ships and submarines require many personnel to support a broad spectrum of operations and maintenance (HCDE, 2000). Optimizing manning requires a detailed examination of the man-machine requirements for operating, maintaining, supporting, fighting, and saving the ship (NRAC, 1996).

In the environment of surface ships and submarines, human engineering is a vital part of total system design in the development of future naval systems. Human systems integration (HSI) is the systems engineering discipline comprising manpower, personnel, training, human engineering, and system safety. HSI discovers and applies information and research about human behavior, abilities, limitations, and other characteristics to the development of systems, devices, environments and jobs for productive, effective, safe, and comfortable use by humans. The subject here is a discipline, the objectives of which are to increase human performance, reduce human error, enhance personnel and equipment safety, and minimize personnel- and training-related costs (Anderson, 1997).

A. MANNING REDUCTION ISSUES

A 1997 *Naval Engineers* journal included the following discussion of human engineering issues in the reduction of ship's manning:

> The underlying rationale of the human engineering strategy for manning optimization involves applying human engineering (HE) and artificial intelligence (AI) techniques to properly distribute the physical and cognitive workloads imposed on shipboard personnel. This permits redistribution of workload between people and machines, and among crew members themselves. It fosters consolidation of existing operator positions, simplification of operator tasks, and optimization of overall ship manning levels. Applying automated human engineering analysis tools to manning has been formally addressed only in recent years. The potential for optimizing manning through improved task simplification and improved man-machine interface design has been demonstrated in a number of applications.
>
> The central human engineering issues in optimizing manning are the proper allocation of functions to man and machine, thus establishing and defining man's role in the system and allocating optimum workloads that maximize human and system performance. A proper function analysis and function allocation will result in the proper assignment of tasks to humans, hardware, or software. It is based on the assessment of the differential capabilities and limitations of humans and machines in terms of the requirements associated with a specific function (Anderson, p. 68).

[1] The sources of most of the material in this section are identified in the list of references.

Humans surpass machines in[2]

- Detecting visual, auditory, or chemical energy;
- Perceiving patterns of light or sound;
- Improvising and using flexible procedures;
- Storing information for long periods and recalling appropriate parts;
- Reasoning inductively; and
- Exercising judgment.

And machines surpass humans in

- Responding quickly to control signals;
- Applying great force smoothly and precisely;
- Storing information briefly and erasing information completely;
- Reasoning deductively;
- Performing repetitive and routine tasks; and
- Handling high complex operations.

A Naval Forces journal (Anderson, 1997) discusses the role-of-man issue and the workload measurement issue:

> With [the above] considerations in mind, the focus of human engineering is on the determination of the role of man in the system, rather than merely allocating functions to human or machine performance.
>
> Another critical issue in applying human engineering analysis techniques to optimal manning is the relationship between manning and workload. The basis for predicting manning requirements must be the workload associated with the roles of humans in system operations. The challenge for the human engineering profession lies in the measurement of workload.
>
> Workload measures and methods…involve human sensory, psychomotor and cognitive capacities, and the demands placed on these by operator tasks inherent in the design of ship systems. While workload measures in the area of physical work, muscular exertion and physical fatigue are certainly of interest, the greatest uncertainty lies in the area of defining workload in tasks that do not require much physical effort, but rather, load the operator in terms of perceptual, cognitive and decision making skills. One existing problem is that workload is not directly observable. What is observable and what ultimately contributes to, or degrades, total system performance is operator task performance in terms of response speed and accuracy. The response time to events and the accuracy of the response are measurable, and will influence total system performance. Workload (including underload and overload) must be inferred from observed performance (p. 68).

B. MANNING OPTIMIZATION TECHNIQUES

One way to improve ship systems is to use the principles, standards, and methods of human engineering to improve their "-ilities": operability, controllability, manageability, usability, maintainability, sustainability, survivability, safety, habitability, installability, reconfigurability, updateability, and supportability (Anderson, 1997). The results of applying the human engineering principles in system design are

> (1) displays [that] are meaningful, readable, integrated, accurate, current, complete, clear, directive, transparent, readily associated with control actions, and responsive to information requirements; (2) controls [that] are reachable, identifiable, operable, consistent, compatible with expectations and conventions, and simple to use; (3) consoles and panels [that] include the required control and display functions, which are arranged in terms of functions, sequence of operations, and priorities; (4) procedures [that] are logical,

[2] Both lists are incorporated in a research report by Calhoun (2000).

consistent, straightforward, and provide feedback; (5) communications [that] are standardized, consistent, intelligible, clear, concise, identifiable, prioritized, and available; and (6) environments [that] are within performance, comfort and safety limits, designed in terms of task requirements, and [reflect] long term as well as short term exposure (Anderson, p. 69).

An example of how displays can affect task performance is illustrated in Figure 13.6-1. The figure shows mean time to complete a combat air patrol (CAP) task in a command-and-control (C2) environment for various console display configurations. The results show that touchscreen was better, by about 3 to 11 seconds, compared with the other display configurations tested (Osga, 1995).

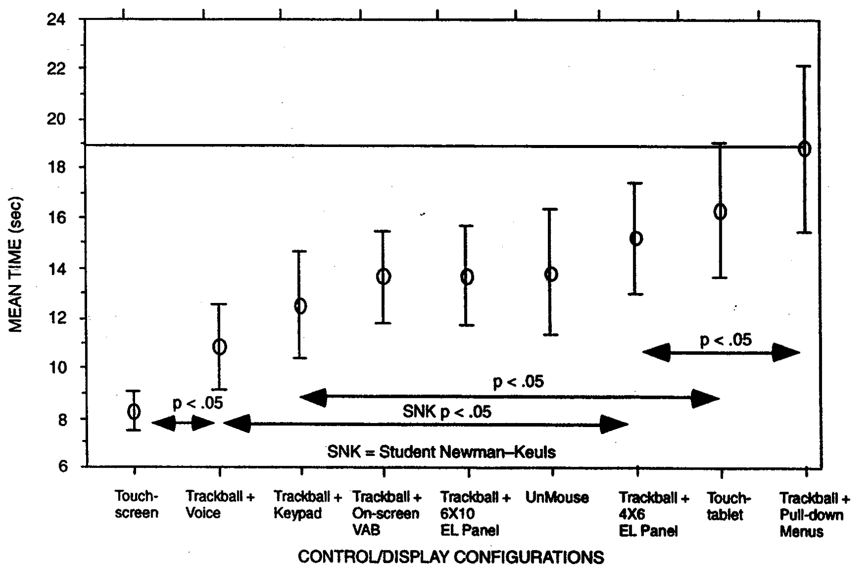

Figure 13.6-1. Mean Completion Time for Combat Air Patrol Task with Various Console Display Configurations (Source: Osga, 1995).

Another way to improve ship systems is to simplify tasks. That involves reducing high driver task demands—physical, cognitive, and perceptual-motor—as much as possible.

> Specific demands include: (a) amount of information to be processed; (b) complexity of the information processing; (c) number of decisions and options to be handled; (d) complexity of actions, (e) needs for interactions with other operators; (f) extent and complexity of communications; (g) task accuracies required; (h) special skills and knowledge required, (i) level of skills such as reading comprehension; (j) level of stress associated with the performance of tasks under representative mission conditions; and (k) time constraints (Anderson, 1997, p. 69).

Ship systems can also be improved by applying AI techniques to develop decision aids that reduce the cognitive workload of ship personnel. The AI system fuses data from multiple sources, and performs correlation, integration, and abstraction tasks to provide a refined picture of a summation, process, or event (Anderson, p. 69). This decision-aiding approach enables fewer operators to handle a greater workload.

Figure 13.6-2 illustrates the benefit of optimizing human workload in system design. The figure shows team workload results in which a traditional Aegis CIC (combat information center) team of 12 and an optimized team of 5 are compared in performing over 100 runs of the same scenario in which the mission involves air defense, tactical ballistic missile defense, and land attack. The *x*-axis shows actual mission time and the *y*-axis displays a measure of workload, a weighted amount of the number of activities going on at any time during the mission. The workload is lower for the much smaller team. That performance outcome is attributed mainly to the design of the optimized team and to ensure that each team member has direct access to the resources needed to accomplish his responsibilities, thus minimizing the need for communications among team members (Human Performance Models Presentation, 1998).

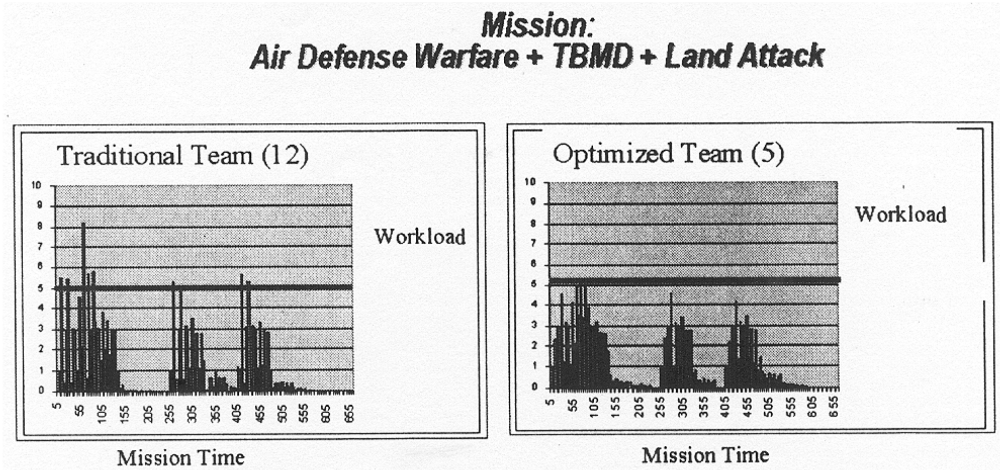

Figure 13.6-2. Simulation Workload Data, Traditional Team vs. Optimized Team in a Command and Control Environment Mission (Source: Human Performance Models Presentation, 1998).

In an ongoing research effort, the Navy is exploring the possibilities of an optimally manned command environment for future ships. This Integrated Command Environment (ICE) test bed involves

- Operator (warfighters) interacting with designers;
- Exploring "what if…?" ideas;
- Evaluating human factors and human-centered technologies;
- Assessing concepts for manning and training;
- Testing the usability and/or performance of individuals, teams, and organizations; and
- Demonstrating visionary concepts.

The control-display results in Figure 13.6-1 and the workload-manning results in Figure 13.6-2 illustrate the prospective benefits from the command concepts research in the ICE test bed. However, personnel reduction in the C2 case in Figure 13.6-2 is mitigated somewhat because the CIC watch standers have collateral duties, which must be done by someone. This, again, underscores the necessity of using the optimized manning approach over a strictly reduced manning approach.

Up to now, human engineering has been applied largely for high-level decision making (mainly C2, which includes sensor data integration and weapons control). Because relatively few people are involved, the potential for manning reduction is less than it would be if automated decision-aiding were focused on lower level decision making (Anderson, 1997) as described by the non-C2 applications below.

C. SMART SHIP PROGRAM

The Navy has an ongoing effort to assess shipboard systems and procedures to identify technologies that save manpower through retrofit of in-service ships and incorporation in future designs (NRAC, 1996; Truver, 1998). The Navy expects to see several payoffs from the Smart Ship and the DD-21 destroyer efforts, including reduced ship's crew by virtual presence (RSVP), damage-control automation for reduced manning, and the all-electric ship.

1. RSVP

Fault-tolerant, intracompartment, wireless, MEMS-based sensor networks will provide real-time, internal shipwide situational awareness (Tertocha, 1999; Ready, 1997). Environment and structural monitoring will include temperature, chemical, humidity, pressure, vibration, and acoustic information.

Machinery health monitoring will include bearings (vibration and temperature), motors and generators, and mechanical components.

Personnel monitoring can include the following information: heart rate, skin temperature, body motion, and body position of damage control team member or other ship's crew.

2. Damage Control

Automating fire protection and fluid system management will reduce the damage control workload. The Damage Control Center will quickly know the location and type of casualty and know which ship's areas to isolate. See Section 13.3 for more information.

3. Electric Ship

Although not initiated as an optimized manning effort, the electric ship design will require fewer propulsion/ maintenance watch standers. See Section 13.2 for more information.

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TECHNOLOGY DATA SHEET
13.6. HUMAN SYSTEMS INTEGRATION

Technology Name **Page**

DATA SHEET 13.6. HUMAN ENGINEERING

Developing Critical Technology Parameter(s)	Manning optimization results from automating functions that machines and software perform better than humans, and applying human engineering principles that involve workplace layout, work procedures, communications, displays, consoles, and control to properly balance human workload. These improve the overall system performance.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	None identified.
Major Commercial Applications	The human-centered approach to systems design has already been adopted by the marine industry, and it is being increasingly adopted by other profit-oriented industries.
Affordability	Optimizing manning means reduced costs of ship ownership. By using virtual presence to reduce workload in DD-21 class ships, it is expected that cost avoidance of at least $2.5B will be achieved during a 35-year life span.

BACKGROUND

The major ownership cost of ships is incurred in operating and supporting them during their lifetime. The dominant cost driver is personnel. Thus, optimal manning is achieved by focusing on human engineering principles during systems development. Total ship systems design and engineering will automate functions that will in turn optimize manning. For example, the DD-21 manning objective is 70 percent less than the traditional DDG baseline—from 320 to about 100.